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Shelter Research 1400-Component Development, Subtask 1424A-Experimental Study of Life Support in Closed Shelters

EXPERIMENTAL EVALUATION OF ENVIRONMENTAL CONTROL SYSTEMS FOR CLOSED SHELTERS

July 1964

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ABSTRACT

This report summarizes the results of an experimental study of oxygen supply and carbon dioxide control systems which are suitable for use in closed shelters for protection against fallout and/or other weapons effects. The most probable reason that would compel closed operation of a shelter and consequent use of an internal life support system is the presence of hot, toxic gases resulting from proximate fires, although this procedure would also be effective against BW and CW agents.

The program objectives are summarized below:

1. Determine the performance characteristics and design requirements for passive carbon dioxide absorption techniques.

2. Verify the state-of-the-art design data for dynamic carbon dioxide absorption systems.

3. Evaluate oxygen regulators now commercially available to determine possible design changes needed to provide apparatus that is more suitable (than the commercial types) for use in closed shelters.

Thirty-six simulated occupancy tests and one human occupancy test were conducted in order to evaluate the performance of passive carbon dioxide absorption methods. Two canister tests were conducted to verify the design data for dynamic carbon dioxide absorption methods. Fifteen regulator manufacturers were contacted in the field survey effort.

The program results are summarized as follows: (for a 24-hour closure period)

1. Oxygen supply can be provided at a cost of about $4.70 per person for smaller shelters (100-man) or about $4.15 per person in larger shelters

(1000-man). A more extensive study is suggested in order to provide specifications, more accurate costs, and installation designs for various size and type shelters.

2. Carbon dioxide concentration can be controlled satisfactorily by the use of Baralyme (or soda-lime at a slight loss in efficiency) in screened panels at a cost of about $4.50 per person.

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INTRODUCTION

1.1 Background

This program was initiated as a follow-on to Contract OCD-OS-62-56 (Environmental Control Systems for Closed Underground Shelters, Ref. 1) and entailed the testing and evaluation of methods for controlling the oxygen and carbon dioxide content of a closed shelter.

The earlier program was a feasibility and parametric study of atmosphere control techniques for use in closed underground shelters with respect to projected cost-effectiveness, as well as a state-of-the-art survey. Life support systems are required whenever the presence of outside fires precludes the supply of ambient air to the shelter. Environmental control systems which were evaluated under the earlier program included all conceivable types of oxygen supply, carbon dioxide and toxic and/or odiferous constituent removal, and temperature-humidity control.

1.2 Objectives and Scope

The objectives of this present contract, hereinafter referred to as the test program, were, in large part, stipulated under the previously referred to contract, hereinafter referred to as the study program.

The study program indicated that three solid absorbents; namely, lithium hydroxide (anhydrous), Baralyme, and soda-lime, are best suited for controlling the concentration of carbon dioxide within a closed shelter. Strope and others (Ref. 2) demonstrated the efficacy of the use of Baralyme for controlling carbon

dioxide concentrations in shelters during manned occupancy tests at the U.S. Naval Radiological Defense Laboratory in 1959.

The study program also indicated that from a standpoint of safety, reliability, and ease of handling, breathing oxygen should be supplied by either chlorate candles or high pressure gas cylinders equipped with a regulator and small flowmeter. Since the gas cylinder method is less expensive than the use of chlorate candles except for small family shelters, the cylinder method was recommended for all shelters occupied by more than five persons.

Based on the above findings it was decided that the test program should experimentally evaluate the performance of solid carbon dioxide absorbents to obtain design information for shelter use. As a further delineation of the program objectives, it was decided that the main emphasis should be placed upon passive absorption methods, since these methods seemed more likely to be used than dynamic systems, which require power. Also, the state-of-the-art, relative to passive absorption phenomenon, was considered less advanced than that for dynamic absorption techniques.

The study program also concluded that the equipment presently available for dispensing oxygen from large high pressure storage bottles is not only too expensive but too complicated for use by the average citizen, especially during periods of high emotional stress. Therefore, it was decided to contact a number of manufacturers of gas regulating equipment to explore the possibility of the commercial development of a closed shelter oxygen regulator - if and when the procurement order might be given.

The listing below reiterates and summarizes the program objectives.

1. Determine design parameters for the use of passive carbon dioxide absorption techniques in closed shelters.
2. Verify the design information for dynamic absorption methods stated in the study contract.
3. Conduct a field survey of regulator manufacturers to learn of possible design changes which would yield a regulator more adaptable to fallout shelter use.

As a final test, the best passive absorbent and most suitable oxygen regulator were to be tested in a human occupancy test. Simulated occupancy tests for carbon dioxide absorption were to be conducted in an 875-cubic foot environmental chamber, and the human occupancy test in a 1000-cubic foot underground shelter.

SECTION 2

TECHNICAL CONSIDERATIONS

2.1 Carbon Dioxide Absorption

2.1.1 Types of Absorbents

The absorbents which were investigated under the test program included Baralyme, soda-lime, and anhydrous lithium hydroxide.

2.1.1.1 Baralyme - Baralyme is a crystalline caustic mixture with the typical composition shown below:

$Ba(OH)_2 \cdot 8H_2O$	20% by weight
$Ca(OH)_2$	80%
KOH	small amount
Mimoza Z dye and ethyl violet	trace
Wetting agent	trace

The barium hydroxide hydrate provides water of crystallization which acts as a binder and also sustains the reaction with the carbon dioxide forming barium carbonate and liquid water as shown below.

$$Ba(OH)_2 \cdot 8H_2O + CO_2 \longrightarrow BaCO_3 + 9H_2O$$

The water formed wets the potassium hydroxide and calcium hydroxide which reacts to form calcium carbonate and liquid water as shown by,

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O$$

The dye is added to provide an indication of when the material is depleted. Fresh material is pink; the color then shifts first to purple and then to blue

as salts of weak acids are formed. The small quantity of wetting agent reduces the tendency to form a caustic dust.

Baralyme is theoretically capable of absorbing 50.3 per cent of its weight in carbon dioxide, liberating 1020 Btu/lb of CO_2 in process. The bulk density of the material is approximately 58 lb/cu ft; the material is commonly supplied from its sole distributor, Thomas A. Edison Industries, in a container similar to a one-quart milk carton holding two pounds of Baralyme, at a total cost of $0.78 or $0.39 per pound.

2.1.1.2 Soda-Lime - Soda-lime has been used as a carbon dioxide absorber since 1918. The latest formulation consists of the constituents listed below.

$Ca(OH)_2$	74.8%	by weight
NaOH	2.5	
KOH	1.2	
Moisture	17.0	
Binder	0.9	

The calcium hydroxide reacts with carbon dioxide in the presence of moisture to form calcium carbonate and liquid water as shown by,

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O$$

The sodium hydroxide also reacts to form sodium carbonate and liquid water as shown by,

$$2NaOH + CO_2 \longrightarrow Na_2CO_3 + H_2O$$

or sodium carbonate hydrate as follows,

$$2NaOH + CO_2 \longrightarrow Na_2CO_3 \cdot H_2O$$

Soda-lime may also be obtained with a dye to indicate relative freshness of the material. Theoretically, soda-lime is capable of absorbing 48.4 per cent of its weight of carbon dioxide. For each pound of carbon dioxide absorbed, 1080 Btu of heat are liberated assuming the water remains a liquid.

The bulk density of soda-lime is approximately 50 lbs/cu ft and is available from the Mallinkrodt Chemical Works and the Dewey and Almy Division of W.R. Grace and Company at a cost of approximately $0.30 per pound in drum quantities.

The toxic or caustic properties of soda-lime, like Baralyme, are attributed to the content of hydroxides.

2.1.1.3 Lithium Hydroxide - Lithium hydroxide is a white crystalline base which has been used in the anhydrous form for carbon dioxide absorption aboard submarines since the 1930's and more recently aboard space vehicles.

Lithium hydroxide reacts with carbon dioxide to form lithium carbonate and water in either the liquid or vapor state as shown below.

$$2LiOH + CO_2 \longrightarrow Li_2CO_3 + H_2O$$

If the water is assumed to evolve in the liquid state, the reaction liberates 1310 Btu of sensible heat per pound of carbon dioxide absorbed; if the more probable reaction to form vapor is assumed the reaction liberates 875 Btu of sensible heat and 435 Btu of latent heat per pound of carbon dioxide absorbed. Theoretically, one pound of lithium hydroxide will absorb 0.92 pounds of carbon dioxide.

The bulk density of lithium hydroxide is 24 lbs/cu ft and is available from the Foote Mineral Company, Lithium Corp. of America, Var-Lac-Oil Chemical Co., and Maywood Chemical Works at a cost of about $4.50 to $5.00 per pound.

Lithium hydroxide is a strong caustic material which will cause burns if it contacts the skin, especially if the skin is moist.

2.1.2 Methods of Use

2.1.2.1 Passive or Screen Method - Passive or static absorption systems for carbon dioxide have been reported in the literature for use in submarines (Ref. 3), aerospace vehicles (Ref. 4), and fallout shelters (Ref. 5). In general, these systems utilize some type of screened panel which exposes a large surface area to the environment, and rely upon natural convection currents to provide contact of the CO_2-laden air with the absorbent crystals.

Many factors affect the performance of such systems. Some of the most significant are listed below (not necessarily in order of importance) followed by a brief discussion of each factor.

1. Type of absorbent
2. Exposed area of absorbent beds
3. Position of bed
4. Thickness of absorbent layer
5. Amount of air circulation
6. Temperature and relative humidity

The type of absorbent used; whether Baralyme, soda-lime, or lithium hydroxide, has a significant effect upon performance due to the differences in the chemical affinities for carbon dioxide as discussed under Section 2.1.1. Also it is

conceivable that the same absorbent may differ from one manufacturer to another, although this factor was not investigated in the test program.

The amount of area of absorbent exposed to the environment has a direct effect upon performance which is intuitively clear. Not so clear, perhaps, is the importance of bed position relative to the internal structure of the shelter. Because of the variation of convection currents from one location to another, bed performance is dependent to some degree upon location.

The bed thickness or the amount of absorbent placed upon each bed affects performance in two ways. The direct or more obvious effect is the increase in theoretical total capacity for carbon dioxide because of the larger amounts of absorbent present. The less obvious effect is the influence upon air circulation through the bed due to the relative thickness or thinness of the bed. Performance is directly affected by the total absorbent crystal area contacted by the shelter air; therefore, thickness may lower unit capacity (lb of CO_2/lb of absorbent) although it may increase total capacity (lb of CO_2 absorbed).

The amount of air circulation has a direct effect upon bed performance because higher circulation rates allow greater quantities of carbon dioxide-laden air to contact the absorbent sites per unit time.

Humidity aids the absorption reaction to the extent that it wets the surface of the crystal allowing more effective contact of gas and retards the reaction in a physical sense because of possible caking.

2.1.1.2 Active or Canister Method - Solid absorbents are often used in packed beds. In this case some means of forcing the carbon dioxide-laden air

through the bed is required. The required air flow rate through an absorbent canister will depend upon the desired carbon dioxide removal rate (number of occupants), the desired carbon dioxide concentration, and the canister removal efficiency as below.

$$v_A = \frac{v_{CO_2} N}{\eta_r C} \tag{1}$$

where, v_A = volume flow rate of air, cfh

v_{CO_2} = CO_2 production rate per person, 0.85 cfh

N = number of inhabitants

η_r = dynamic removal efficiency, decimal

C = Volume concentration of CO_2 in shelter air, decimal

The dynamic removal efficiency will vary with time as the absorbent is consumed. Usually, as shown in Figure 6 the removal efficiency will remain high (in excess of 0.85 or 0.90) for most absorbents until the "breakthrough" point in time is approached. The breakthrough time may be defined as the time at which the effluent concentration reaches a predetermined value. The breakthrough point is sometimes thought of as an indication that the absorbent is almost exhausted. Obviously, the overall utilization efficiency obtained is, to some degree, dependent on the breakthrough point specified.

The volume of an absorbent bed is dependent upon the carbon dioide removal rate and time of operation, the theoretical (stoichiometric) capacity and density of the absorbent, and the utilization efficiency as shown below:

$$V_a = \frac{m_{CO_2} Nt}{A_T \eta_u \rho_a} \tag{2}$$

where, V_a = volume of absorbent canister, cu ft

m_{CO_2} = weight flow rate of CO_2 production per person, 0.1 lb/hr

ρ_a = bulk density of the absorbent, lb/cu ft

N = number of inhabitants

t = time of operation, hours

A_T = theoretical capacity of particular absorbent, $lb_{CO_2}/lb_{abs.}$ (See Section 2.1.1)

η_u = utilization efficiency, decimal

The utilization efficiency is dependent upon many factors including air velocity, bed length, and humidity. Values as high as 0.85 to 0.95 are commonly obtained with good canister design. Reasonable length to diameter ratios and high efficiencies for absorbent canisters are obtained by stipulating superficial air velocities through the canister of about 0.5 fps. (For more information on canister design see study report, Section 4.2.1 and Ref. 6)

Based on equations (1) and (2), the dimensions for two absorbent canisters (one for soda-lime and the other for lithium hydroxide) were calculated and tested as described under Section 3.1.2 of the test report.

2.2 Oxygen Supply

Under the study contract it was determined that from a standpoint of safety, reliability, and ease of handling, oxygen could best be supplied by high pressure gas cylinders equipped with regulators and flowmeters. The study contract also

concluded that the development of convenient and inexpensive dispensing equipment to be used in conjunction with the cylinders was required. The presently available equipment was judged too expensive and too complicated to be operated by the average citizen during periods of high emotional stress.

For the above reasons it was decided that several regulator manufacturers would be contacted concerning the development of a regulator more suitable to fallout shelter applications. Under the test program the following manufacturers were sent letters of inquiry:

Bastian Blessing Company
4201 W. Peterson Avenue
Chicago 46, Illinois

Crane Company
Industrial Products Group
4100 S. Kedzie Avenue
Chicago 32, Illinois

Davis Regulator Company
2541 S. Washtenau Avenue
Chicago 8, Illinois

Firewel Company, Inc.
3679 Broadway
Buffalo, New York

Fluid Power, Inc.
663 Aurora Road
Macedonia, Ohio

Grove Valve & Regulator Company
6529 Hollis Street
Oakland 8, California

Harris Calorific Sales, Inc.
108 South Avenue W
Cranford, New Jersey

Hoke Incorporated
10 Tenakill Park
Cresskill, New Jersey

Leslie Company
714 Grant Avenue
Lyndhurst, New Jersey

Linde Company
Division of Union Carbide Corp.
270 Park Avenue
New York City, New York

Liquid Carbonic Medical Gases
Division of General Dynamics Corp.
3112 S. Kedzie Avenue
Chicago, Illinois

Modern Engineering Company
3417 Pine Blvd
St. Louis, Missouri

Pioneer-Central
Division of Bendix Aviation Corp.
Zone 1
Davenport, Iowa

The Powers Regulator Company
Skokie, Illinois

Scott Aviation Corp.
1314 Depew Avenue
Lancaster, New York

Victor Equipment Company
844-50 Folsom Street
San Francisco, California

Of the above listed companies, only the Bastian-Blessing Company, Scott Aviation Corp., and Linde Company furnished noteworthy information. The following is a paraphrasing of each company's viewpoint on the development of a closed shelter oxygen regulator:

1. Bastian-Blessing Co. - A regulator capable of supplying oxygen for 100 persons could be developed which would cost about $8.00 each in large quantity lots. The regulator would have dimensions of about 6 in. by 4 in. The cylinder connection (standard CGA 540) would be at the bottom middle and the outlet at the top middle. At one end would be a stem with an adjusting knob to be set according to the number of the people in the shelter. At the other end would be a piston-type pressure gage which would provide a rough indication of the amount of oxygen remaining in the cylinder. The outlet flow would decrease only slightly as cylinder pressure decreased.

2. Linde Company - Essentially standard regulators could be used depending upon the particular size of the shelter in question. Single stage regulators could be used with only a slight sacrifice of outlet flow rate accuracy. Changes in the outlet flow could be provided by either varying the upstream pressure to a one-size orifice cr using a discretely variable orifice plate with the same upstream pressure.

Oxygen supply for extremely large shelters (over 500 occupants) should give consideration to methods for distributing the oxygen throughout the shelter. In particular, attention is called to the fact that a high rate of flow, as would be required for large capacity shelters, would create possibly disconcerting or undesirable noise levels. For this reason the use of low cost muffling devices is suggested.

3. Scott Aviation Corp. - By standardizing on one size of regulator, production cost economies would result and the cost per regulator would decrease. Also, in the installations themselves, it would be more economical and desirable to use smaller multiple regulators located at different points. With a multiple regulator system there would be a safety factor if one regulator should malfunction.

From the above information obtained in limited correspondence and personal contact, two facts emerge:

1. Oxygen regulators which are now commercially available can be readily modified so as to incorporate recommended changes, thus providing lower cost and greater adaptability to fallout shelter applications.

2. The types of regulators and associated oxygen storage and dispensing equipment should be "custom-selected" for each size-class of shelter.

The time allotted under both the study and the test program has allowed only a superficial analysis of the oxygen supply problem. To insure the optimum selection of oxygen equipment and also furnish accurate cost information, a separate survey and study program is suggested.

SECTION 3

EXPERIMENTAL EVALUATIONS

3.1 Carbon Dioxide Absorption Tests

Carbon dioxide absorption tests were conducted using both passive and active methods. These tests are described in Sections 3.1.1 and 3.1.2, respectively. Passive absorption systems were utilized in both the simulated occupancy tests (Section 3.1.1) and human occupancy tests (Section 3.2).

3.1.1 Passive Method

This section and the following subsections describe the simulated occupancy tests conducted in the 875-cubic foot environmental chamber.

3.1.1.1 Description of Tests - In all tests conducted under this program the performance of a passive absorption bed was indicated by the absorption unit capacity or weight of carbon dioxide absorbed per weight of absorbent present. As previously stated, the performance of a passive absorption bed is significantly affected by several factors including the type of absorbent, the area and position of the bed, the thickness of the absorbent layer, the amount of air circulation, and temperature and relative humidity.

An initial series of tests were conducted with the amount of air circulation constant at a minimal rate (see Section 3.1.1.2), an effective temperature of approximately 85°F, and a bed thickness of 1/2 inch. These tests are best represented by the matrix shown as Table 1. The numbers correspond to the test result chart shown in Section 3.1.1.3. As shown, some of the tests were repeated to verify reproducibility of the results.

TABLE 1

DESCRIPTION MATRIX FOR INITIAL SERIES OF

PASSIVE ABSORPTION TESTS

All tests conducted at 85°F ET with absorbent spread 1/2-inch thick and minimal air circulation.

		Absorbent		
Area	Position	LiOH	Baralyme	Soda-Lime
One Bed	Lower	1, 2	24	23
	Upper	3	20	17
Two Beds	Lower	29	8, 9	22
	Upper	18	19	21
Three Beds	Lower	10	5, 6, 7	14, 15
	Upper	18	11	13, 16

TABLE 2 DESCRIPTION MATRIX FOR SECOND SERIES OF PASSIVE ABSORPTION TESTS

All tests conducted at 85°F ET with Baralyme

	Thickness		
Area	1/4"	1/2"	3/4"
One Bed	30, 32	(20)	31
Two Beds	27, 33*	(19) 35*	28
Three Beds	25	(11)	34

*Signifies starting condition of 72°F DBT and 58°F WBT.

After tests for the 18 cells of the initial matrix were completed, another test matrix was formulated and completed. Table 2 indicates that this series of tests was intended to investigate the effect of thickness upon performance, since the initial series had indicated that Baralyme beds in the top position was an optimum combination for these two factors. Only 6 tests were required to complete this matrix since 3 cells marked with parentheses were carried over from the initial matrix.

To determine the effect of temperature-humidity upon performance two tests, Nos. 33 and 35, were conducted without preconditioning the environmental chamber to 85°F ET. One test was conducted using a bed thickness of 1/2 inch, and the other using a thickness of 1/4 inch in order to allow identification of any possible interaction between thickness and effective temperature.

Two final tests, Nos. 36 and 37, were then conducted at 85°F ET using 1/2-inch thick Baralyme beds with double the input flow rate of carbon dioxide. To determine the effect of increased air circulation, test number 37 utilized an ordinary 10-inch electric fan to provide a higher degree of air movement.

3.1.1.2 Test Apparatus - Figure 1 shows the test configuration utilized during all simulated occupancy tests. Since the main portion of the environmental test chamber was approximately 500 cubic feet in volume (excluding the volume of the air lock) a nominal manned capacity of six men (allowing a per person free volume of 85 cubic feet) was assigned to the chamber. Assuming a carbon dioxide production rate of 0.85 cubic ft/hr per person a carbon dioxide flow rate of about 5 cfh was established for all tests with the exception of tests numbered 36 and 37, as stated in the preceding section.

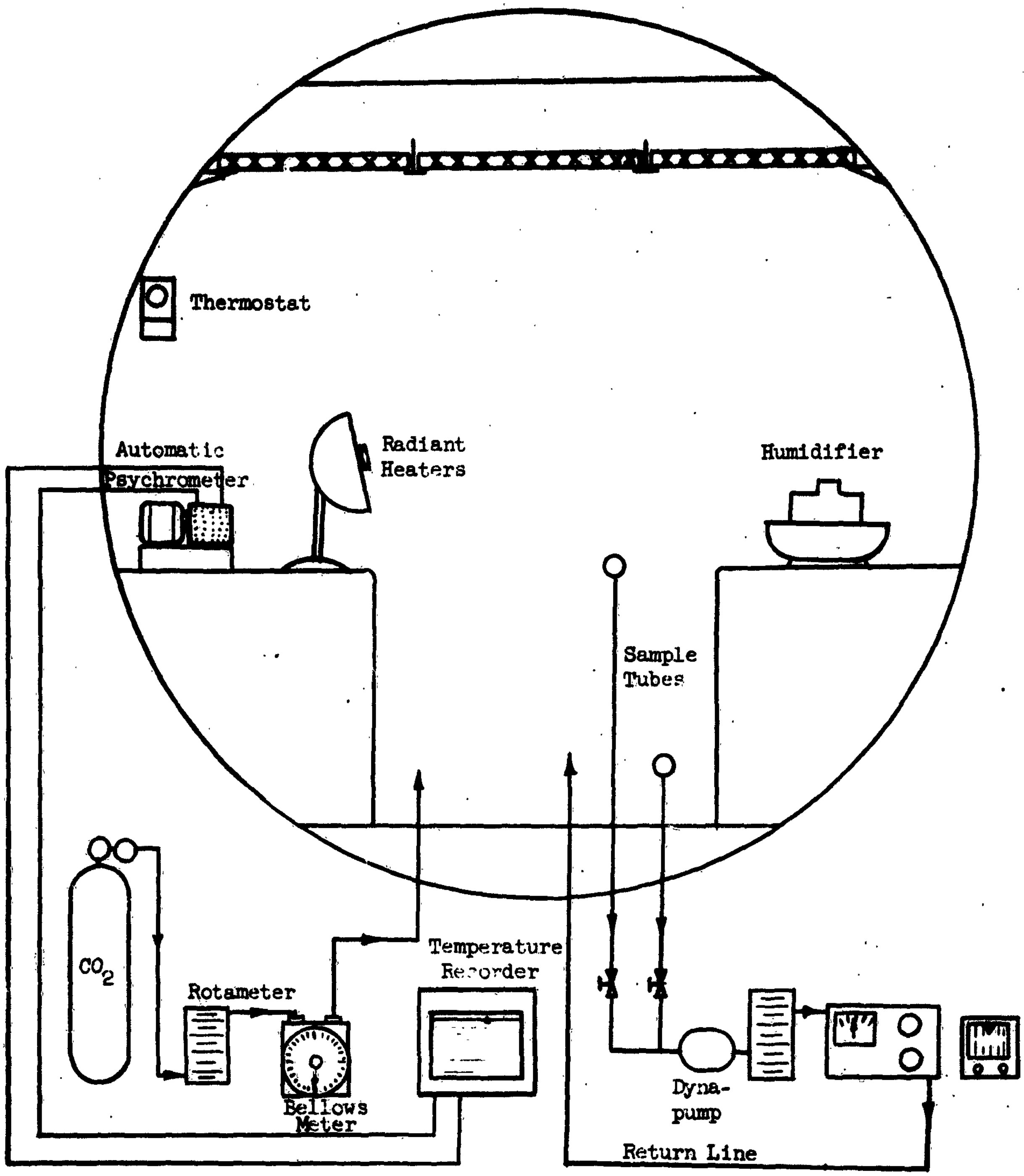

Figure 1 EXPERIMENTAL SET-UP FOR SIMULATED OCCUPANCY PASSIVE ABSORPTION TESTS

The carbon dioxide was released into the chamber by means of a length of flexible tubing with several pin holes so as to diffuse the gas flow, and thereby reduce the magnitude of forced convection currents.

A Brooks Purge Meter was used to control the rate of flow at 5 cfh and a Sprague Bellows Meter was used to measure total flow. Concentration of carbon dioxide was measured by means of a MSA Lira Infrared CO_2 Sensor (0 to 4 per cent) and continuously recorded on a Leeds and Northrup Type G Strip Chart Recorder. A small diaphragm pump was used to draw and return a sample of gas from either of two locations in the test chamber.

Electric radiant heaters (controlled by a thermostat) and both atomizing and vaporizing humidifiers were incorporated to maintain the required effective temperature of 85°F. A Brown Instruments Multipoint Recorder was used in conjunction with thermocouples and an automatic psychrometer to provide a permanent record of temperature and relative humidity.

The absorbent beds consisted of simple wooden frames with 1/4-mesh fiberglass-coated screens. Dimensions of the effective area were 1.5 feet by 2.5 feet. As an example, these frames were capable of holding 8 pounds of Baralyme when it was spread to a thickness of 1/2 inch.

3.1.1.3 Test Procedures - All simulated occupancy tests essentially followed the procedures outlined below:

1. Establish the required temperature and humidity (85°F ET in most cases).
2. Select the predetermined number of absorbent screens; either one, two, or three.

3. **Weigh and load the desired amount of the particular absorbent.**

4. **Place the loaded screen(s) in the desired position(s).**

5. **Set indicating and recording equipment to measure wet and dry bulb temperatures, concentration and total flow of carbon dioxide.**

6. Meter the desired flow rate of carbon dioxide into the chamber (5 cfh in most cases).

7. Continue test until concentration of carbon dioxide reaches 4 per cent.

8. Reweigh the absorbent and note color change, if any.

9. Plot continuous record of carbon dioxide on graph with condensed time scale (concentration vs. time).

3.1.1.4 Test Results - A syncpsis of the test results is difficult to present in a concise form because of the nature of the passive absorption phenomenon. In many of the tests a plot of carbon dioxide concentration versus time shows a generally logarithmic form until an inflection point occurs at a point in time which may justifiably be considered as the breakthrough time. Such a test was test number 7 (three one-half panels of Baralyme in the upper position). The plot is shown as Figure 2. However, many of the tests did not produce results yielding this type of plot. For example, the plot shown as Figure 3, test number 27 (two one-quarter-inch panels of Baralyme in the upper position) obviously does not resemble the plot of Figure 2.

As an initial step in reducing the test data, Table 3 was compiled. As shown, this table presents the time in hours which were required for the concentration of carbon dioxide to reach each of five ascending concentrations. Some of the earlier tests did not obtain the higher concentrations because the over-night automatic recording technique had not yet become established. Test Number 26 was a test of an active canister system and is discussed under Section 3.1.2.

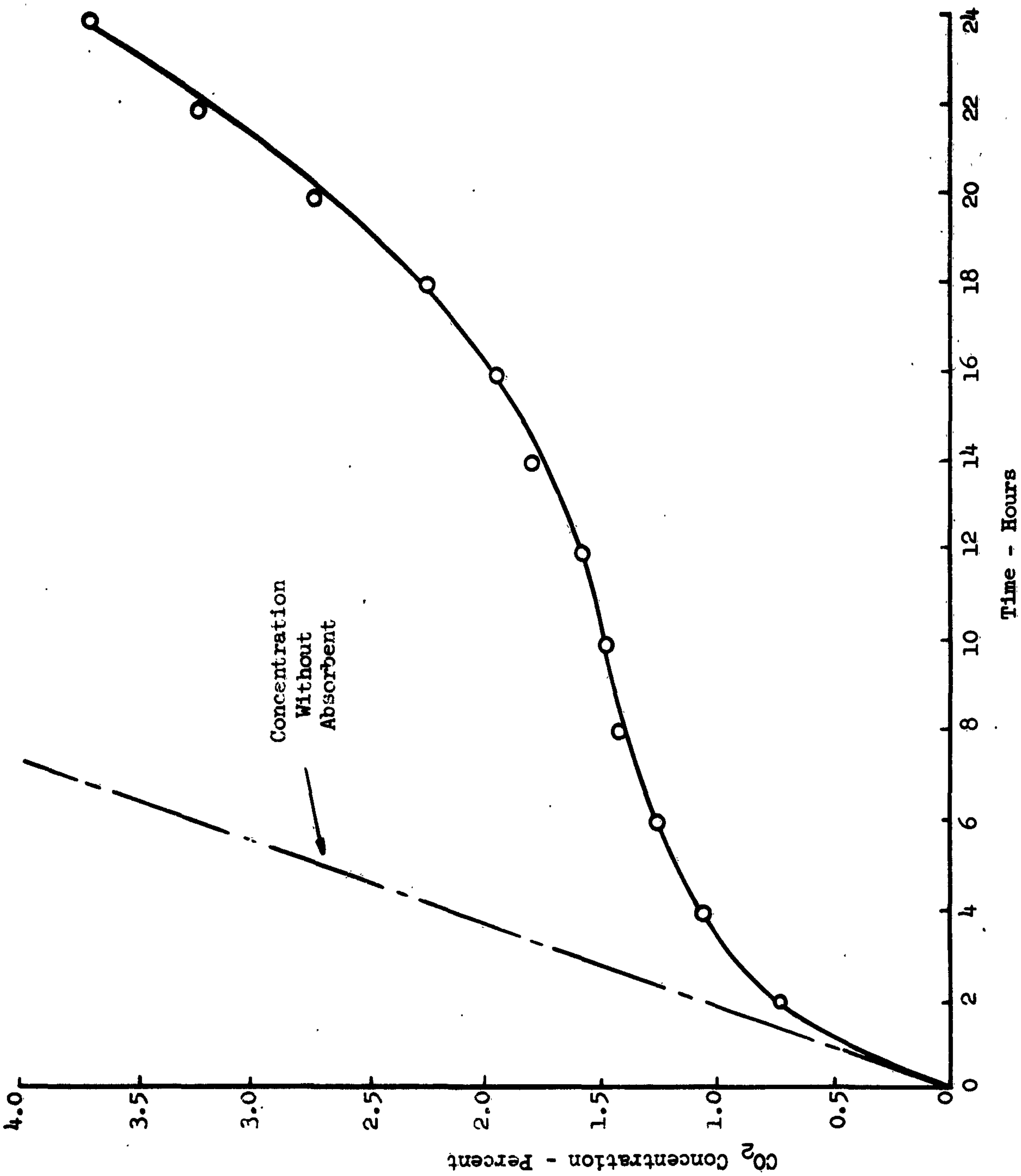

Figure 2 CHAMBER CO_2 CONCENTRATION VS. TIME FOR TEST NO. 7

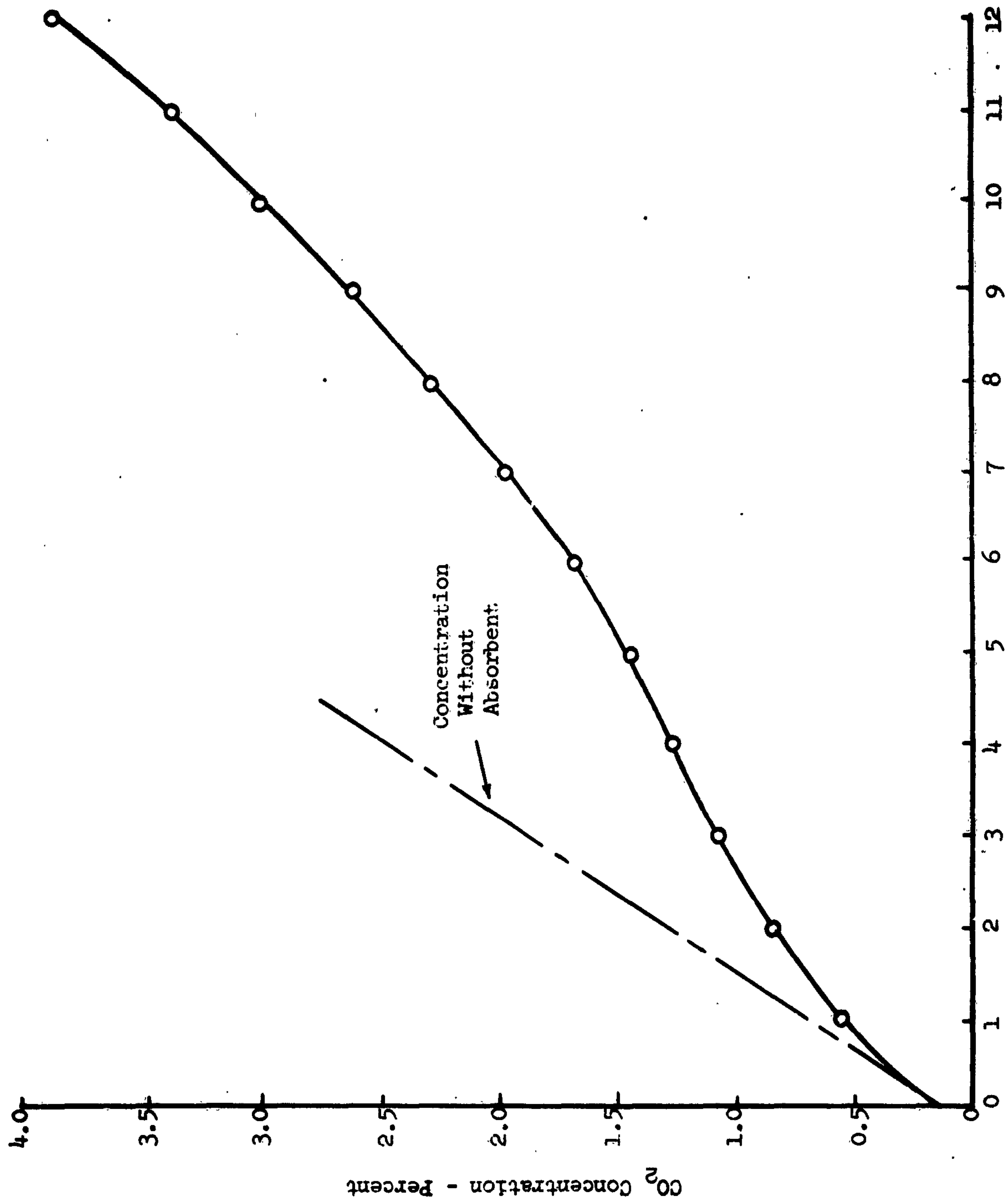

Figure 3 CHAMBER CO_2 CONCENTRATION VS. TIME FOR TEST NO. 27

Table 3 **SUMMARY DATA FOR PASSIVE ABSORPTION TESTS**

Test No.	Average CO_2 Flow Rate (cfh)	Hours to Reach CO_2 Concentrations 0.5%	1.0%	2.0%	3.0%	4.0%
1	4.62	0.5	1.5	3.25	5.0	7.0
2	4.9	0.85	1.75	----	---	---
3	4.9	0.8	1.75	----	---	---
4	4.9	0.75	1.7	Calibration Check		
5	5.0	0.95	2.75	----	---	---
6	5.0	1.0	2.75			
7	4.63	0.55	1.75	16.5	21.3	24.75
8	5.05	1.3	2.2	7.75	13.4	17.0
9	5.4	1.0	2.25	9.25	16.25	20.5
10	5.48	0.9	3.25	15.25	-----	-----
11	5.79	1.1	5.5	17.25	21.25	24.75
12	4.92	1.1	4.0	19.0	26.75	33.0
13	5.02	0.75	2.0	6.5	11.4	-----
14	4.93	0.75	1.9	6.5	11.75	17.6
15	4.96	0.95	3.0	12.5	16.85	20.0
16	4.86	1.0	3.5	15.0	20.0	23.5
17	5.05	0.75	1.95	4.75	8.4	11.75
18	5.11	0.9	2.25	9.0	16.5	22.2
19	4.96	0.9	2.45	10.25	15.1	18.0
20	4.96	0.75	1.85	4.7	8.4	12.0
21	5.02	0.9	2.6	10.25	14.4	17.3
22	4.88	0.9	2.4	8.75	14.1	17.1
23	4.96	0.7	1.7	4.4	7.9	11.25
24	4.85	0.85	2.0	5.2	8.75	12.0
25	5.88	0.80	2.8	9.75	12.5	15.75
26	8.79	10.0	Canister Test			
27	5.33	0.95	2.7	7.0	9.9	11.25
28	4.82	0.8	2.5	9.55	16.0	20.9
29	4.97	0.8	2.2	8.2	16.9	23.2
30	5.00	0.6	1.6	4.3	7.0	9.25
31	5.37	0.9	2.0	5.1	9.5	14.1
32	5.01	0.65	1.7	4.3	6.9	9.25
33	4.94	0.9	2.25	6.5	10.35	13.0
34	5.04	0.9	2.6	15.5	27.0	32.5
35	4.79	0.8	2.05	6.6	15.0	19.4
36	9.88	0.5	1.0	2.5	4.5	7.5
37	10.0	0.95	2.0	4.55	6.65	8.5

In any test if no absorbent were present the concentration resulting at any given time is dependent upon the chamber volume and the input flow rate of carbon dioxide, as shown by

$$C = \frac{v_{CO_2} \cdot t}{V} \times 100 \qquad (3)$$

(neglecting the effects of compression)

where,

C	=	volume concentration of CO_2, per cent
v_{CO_2}	=	average input flow rate of CO_2, cfh
t	=	time, hours
V	=	total volume of chamber, cubic feet

It was decided to eliminate the effect of both chamber volume (so that the results could apply to a closed space of any size), and input flow rate(so that the variations in flow rate due to difficulty in adjusting the carbon dioxide metering valve are unimportant). Therefore, the time intervals shown in Table 3 were converted to weights of carbon dioxide absorbed by means of the following formula.

$$W_c = v_{CO_2} t_c \rho - CV\rho \qquad (4)$$

where

w_c	=	weight of absorbed CO_2 at any particular concentration, pounds
v_{CO_2}	=	average input flow rate of CO_2, cfh
t_c	=	time required to reach any particular concentration hours
ρ	=	density of CO_2, 0.114 lbs/cu ft at 85°F

C	=	concentration of CO_2 in test chamber
V	=	actual chamber free volume, 875 cu ft

Table 4 shows the results of this conversion. Also shown in Table 4 is the mean weight of carbon dioxide absorbed for each test. The simple formula presented below is perhaps the best way to communicate the meaning of the last column in the table.

$$\overline{W}_c = \frac{\sum_{c=0.5}^{4.0} W_c}{5}$$

where $\overline{W}_c$ = mean weight of absorbed CO_2 for each test, pounds

W_c = weights of CO_2 absorbed at each concentration (0.5%, 1.0%, 2.0%, 3.0%, 4.0%), pounds

By the use of the mean weights it was possible to compare test results by use of one single value which was a best estimate of the results of that test. The use of the mean thereby softened the effect of the shape of each curve which would have caused a bias in test interpretation had any one particular concentration been used in test comparisons.

The mean weights from Table 4 were then compared by use of a matrix similar to the one used in setting up the experimental methodology as described under Section 3.1.1.1. A matrix containing the mean weights from the initial series of tests (to determine optimum absorbent, location and the effect of bed is presented as Table 5.

As shown, averages of the means for all rows and columns were calculated in order to compare the effect of area, absorbent, and location without bias due to interactions.

Table 4 MEAN WEIGHTS OF ABSORBED CO_2 FOR PASSIVE ABSORPTION TESTS

Test No.	Mean Weights of CO_2 Absorbed at CO_2 Concentrations					Average Mean Weights
	0.5%	1.0%	2.0%	3.0%	4.0%	$\overline{W}_c$
1	-0.235	-0.207	-0.283	-0.359	-0.303	-0.277
2	-0.083	-0.025	-----	-----	-----	-0.054
3	-0.053	-0.020	-----	-----	-----	-0.036
4	-- Calibration Check					
5	0.040	0.570	-----	-----	-----	0.305
6	0.200	0.570	-----	-----	-----	0.385
7	-0.208	-0.073	6.714	8.250	9.073	4.751
8	0.249	0.269	2.466	4.721	5.796	2.700
9	0.116	0.387	3.699	7.011	8.629	3.968
10	0.063	1.032	7.531	-----	-----	3.200
11	0.101	2.005	7.424	8.611	9.524	5.533
12	0.118	1.246	8.661	12.011	14.519	7.311
13	-0.069	0.147	1.724	3.531	-----	1.330
14	-0.077	0.070	1.658	3.611	5.901	2.232
15	0.038	0.698	5.073	6.535	7.318	3.932
16	0.055	0.941	6.315	8.088	9.029	4.886
17	-0.066	0.125	0.739	1.843	2.774	1.083
18	0.025	0.313	3.247	6.619	8.825	3.806
19	0.010	0.387	3.800	5.545	6.187	3.186
20	-0.074	0.048	0.662	1.757	2.795	1.037
21	0.016	0.490	3.870	5.248	5.910	3.107
22	0.001	0.337	2.872	4.851	5.457	2.706
23	-0.102	-0.036	0.492	1.474	2.371	0.839
24	-0.028	0.108	0.880	1.845	2.644	1.089
25	0.037	0.879	4.540	5.386	5.897	3.348
26	-- Canister Test					
27	0.078	0.643	2.258	3.022	2.845	1.769
28	-0.051	0.379	3.252	5.799	7.494	3.373
29	-0.045	0.248	2.650	6.582	9.154	3.718
30	-0.156	-0.085	0.456	0.997	1.282	0.498
31	0.052	0.226	1.127	2.823	4.641	1.774
32	-0.127	-0.026	0.450	0.948	1.293	0.509
33	0.008	0.269	1.717	2.779	3.331	1.621
34	0.018	0.496	6.910	12.520	14.683	6.925
35	-0.061	0.121	1.608	5.198	6.385	2.650
36	0.064	0.128	0.820	2.075	4.457	1.509
37	0.584	1.282	3.192	4.588	5.700	3.069

Table 5 ANALYSIS MATRIX FOR INITIAL SERIES OF PASSIVE ABSORPTION TESTS

Totals	Area	Position	Absorbent		
			LiOH	Baralyme	Soda-Lime
4.00	One Bed	Lower	*	1.09	0.80
		Upper	*	1.03	1.08
20.46	Two Beds	Lower	3.71	3.96	2.70
		Upper	3.80	3.19	3.10
29.59	Three Beds	Lower	3.20	4.75	3.93
		Upper	7.30	5.53	4.88
		TOTALS	18.01	19.55	16.49

$\Sigma_L = 28.14$

$\Sigma_i = 29.91$

*Insufficient Data

AVERAGE MEAN WEIGHTS:

$$\left.\begin{array}{l} \text{One Bed} = \dfrac{4.0}{4} = 1.0 \\ \text{Two Beds} = \dfrac{20.46}{6} = 3.41 \\ \text{Three Beds} = \dfrac{29.59}{6} = 4.93 \end{array}\right\} \text{Area}$$

$$\left.\begin{array}{l} \text{Upper Position} = \dfrac{29.91}{8} = 3.74 \\ \text{Lower Position} = \dfrac{24.14}{8} = 3.02 \end{array}\right\} \text{Location}$$

$$\left.\begin{array}{l} \text{LiOH} = \dfrac{18.01}{4} = 4.5 \\ \text{Baralyme} = \dfrac{19.55}{6} = 3.26 \\ \text{Soda-Lime} = \dfrac{16.49}{6} = 2.75 \end{array}\right\} \text{Absorbent}$$

Comparison of the averages for each absorbent shows a rank ordering in decreasing effectiveness of (1) lithium hydroxide, (2) Baralyme, (3) soda-lime. The order is not surprising in itself, but the relative closeness of the performance of each absorbent is contrary to expectations because lithium hydroxide should have a much higher per pound capacity for carbon dioxide than either Baralyme or soda-lime (see Section 2.1.1). Since anhydrous lithium hydroxide costs about ten times as much as either Baralyme or soda-lime, it appears that the increase in performance would not be worth the cost. Greater quantitites of Baralyme or soda-lime could easily be used to compensate for the slight performance decrement. Also, anhydrous lithium hydroxide had a prohibitive tendency towards dusting (previously reported under the study contract) which would preclude its recommendation for closed shelters on this characteristic alone.

Comparison of the averages of the means for the two locations shows a definite advantage in the upper position. This is not an unexpected finding because of the tendency for warmed air (the heaters were placed nearer the floor level to simulate location of human occupants) to rise and create more circulation nearer the ceiling than the floor. The finding is certainly a desirable one for it leads to the recommendation that the absorbent panels be placed near the ceiling, a location which is more convenient from the standpoint of both conserving floor space and safety.

The averages of mean weights for each of the three panels (areas) shows that the amount of carbon dioxide absorbed increases at a higher ratio than would be predicted on the basis of a directly proportional weight ratio. In other words, two panels should absorb twice as much carbon dioxide as one panel,

and three panels should absorb three times as much as one panel and 1-1/2 times as much as two panels. However, the data indicates that two panels remove 2.5 times as much as one panel, and that three panels absorb 1.9 times as much as two panels and 4.8 times as much as one panel. These ratios suggest that area changes have greater than a direct linear effect. The second series of tests was designed to verify the effects of changes in area upon performance.

This second series was designed also to determine the effect of bed thickness. Baralyme was used as the absorbent in all remaining tests because of its superior comprehensive performance, as described previously. The completed test matrix with the appropriate mean weights of absorbed carbon dioxide filled in the corresponding matrix cells is shown as Table 6.

These results confirm those of the previous test series; that is, two panels absorb 2.5 times the amount of carbon dioxide as does one panel, and three panels absorb 1.9 times as much as two panels, or 4.8 times as much as one panel - irrespective of bed thickness.

The fact that area changes do not affect bed performance in a directly linear manner may be explained by considering the following two _a priori_ relationships.

1. The rate at which the absorption reaction proceeds is directly (though not linearly) proportional to the concentration of carbon dioxide existing in the chamber.
2. If the area (number of ititial active sites) is increased by a ratio, $\underline{r}$, the number of active sites resulting - after a finite time of exposure to the absorbate - may be as high as $\underline{r}^2$, due to the existance of finite diffusion rates into the absorbent crystals.

Table 6 ANALYSIS MATRIX FOR SECOND SERIES OF PASSIVE ABSORPTION TESTS

	Thickness			
Area	1/4-inch	1/2-inch	3/4-inch	TOTALS
One Bed	0.5	1.03	1.77	3.30
Two Beds	1.77	3.19	3.37	8.30
Three Beds	3.35	5.53	6.92	15.80
TOTALS	5.62	9.75	12.06	27.40

AVERAGE MEAN WEIGHTS:

$$\left.\begin{array}{lcl} \text{One Bed} & = \dfrac{3.3}{3} = & 1.1 \\ \text{Two Beds} & = \dfrac{8.33}{3} = & 2.77 \\ \text{Three Beds} & = \dfrac{15.80}{3} = & 5.27 \end{array}\right\} \text{Area}$$

$$\left.\begin{array}{lcl} \text{One-Fourth Inch} & = \dfrac{5.62}{3} = & 1.87 \\ \text{One-Half Inch} & = \dfrac{9.75}{3} = & 3.25 \\ \text{Three-Fourths Inch} & = \dfrac{12.06}{3} = & 4.02 \end{array}\right\} \text{Thickness}$$

The first of the above relationships explains an advantage of smaller areas - because the concentration of carbon dioxide attains higher values in less elapsed time for smaller areas. The second relationship is an explanation of the advantage possessed by larger areas, as compared to smaller areas. The second relationship also states that this advantage varies between a value equal to r and a value equal to r^2. The advantage actually resulting (for larger areas) is dependent primarily upon time and the assumption of a previously determined cut-off absorbate concentration (4 per cent in all tests). However, the larger area advantage can never be less than the direct area ratio if thickness is the same. The larger area advantage would be only proportional to r if the reactions for all tests had proceeded to completion.

Considering the thickness factor in the test matrix it is seen that doubling the thickness results in an increase of only 1.74 times in absorption capacity. Similarly, increasing the thickness by one-half increases the absorbed weight of carbon dioxide by a factor of only 0.27.

This result is readily explained by the decrease in exposed area per unit weight which results from the use of thicker layers of absorbent. Also, any possible circulation through the bed is restricted by the use of thicker beds.

Tests numbered 33 and 35 were the tests in which the test chamber was not preconditioned to 85°F ET. Instead the initial conditions were the laboratory temperatures of 72°F DBT and 58°F WBT. Although the relative humidity rapidly increased from its initial value of 41 per cent to over 90 per cent the overall performance of the panels, as indicated by the mean weights of absorbed carbon dioxide, was below those for the comparable 85°F ET tests. This indicates that

high relative humidities aid the absorption phenomenon more than they hinder it as discussed in Section 2.1.2.1.

Test number 36 was conducted using an input flow rate of approximately double that used in the previous tests. The mean weight of absorbate, 1.5 lbs, was approximately one half the mean weight of absorbate for the comparable normal input rate test, namely, 3.2 lbs for test number 19. Note that this indicates that the "average" time of this test was only one-fourth as long as that of test number 19 (see Table 3). This result again confirms the time effect of diffusion for an absorption reaction which does not have sufficient exposure time to proceed to equilibrium.

Test number 37 was also conducted with a double input rate but in this test an electric fan was used to produce a high degree of circulation, whereas in all previous tests forced circulation was held to minimal values. This result, mean absorbate weight of 3.1 lbs, shows that higher circulation allows more of the carbon dioxide-laden air to contact active absorbent sites per unit time, similar to the effect of equation(1), Section 2.1.1.2.

3.1.2 Active Method

Two tests of canister or active systems were conducted in the test program. The first test used soda-lime in a polyethylene drum external to the test chamber, and the second test used anhydrous lithium hydroxide in a metal canister inside the test chamber.

3.1.2.1 Test Apparatus and Procedures - The soda-lime test used the experimental set-up shown in Figure 4. The mixing system shown was used so that a cylinder of pure carbon dioxide could be used. The piping of the set-up was

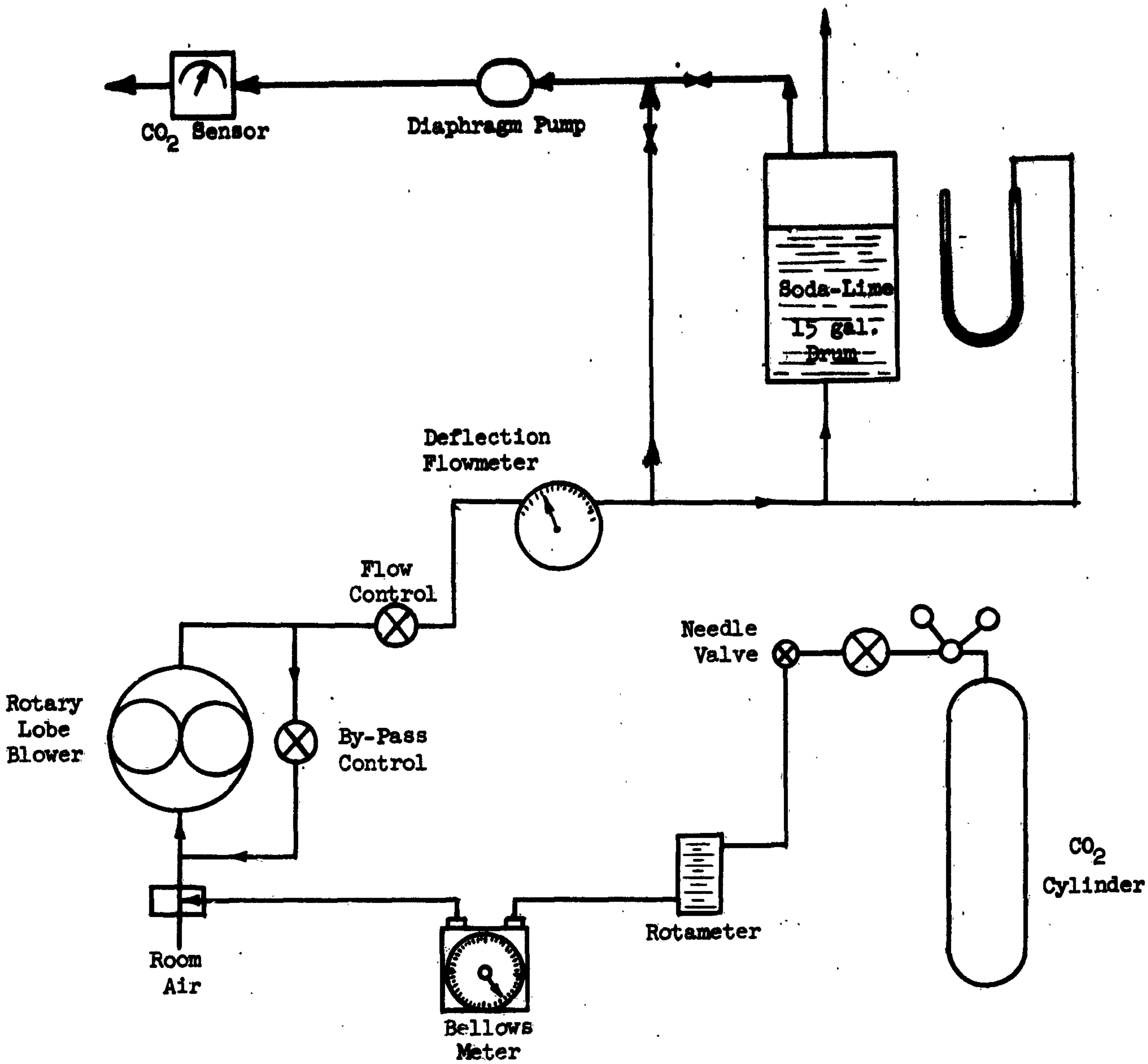

Figure 4 EXPERIMENTAL SET-UP FOR FIRST ACTIVE ABSORPTION TEST

such that the concentration of carbon dioxide at either the inlet or exhaust to the absorbent canister could be measured alternately.

A Sutorbilt 50-cfm rotary-lobe blower was used as the air circulating device. A Seico 0 to 50 cfm flowmeter measured the flow rate of air through the canister.

The 15-gallon polyethylene drum was selected as an example of a commercially available commodity which could be economically obtained and modified by the average citizen. The absorbent could also be packaged in such a container complete with fittings if the demand were sufficient to entice production. The dimensions of a 15-gallon drum (15 in. diameter x 20 in.) qualified it for use as a 10-man canister, as determined in the study program.

Soda-lime was selected as the absorbent because it is the lowest cost absorbent and therefore the most likely to be used in a canister system. Sixty-one pounds were loaded into the polyethylene drum at the start of the test. (Sixty-eight pounds were originally specified but were not available.) The flow rate of carbon dioxide through the rotameter and bellows meter was adjusted to the nominal equivalent of 10 men, which is 8.5 cfh. To maintain the inlet carbon dioxide concentration at one per cent of the flow through the canister was adjusted to 850 cfh or about 14 cfm. This assumes a constant canister removal efficiency of 100 per cent. (See Section 2.1.2.2.)

The lithium hydroxide canister test used the test set-up shown in Figure 5. In this test the 16 in. diameter x 11 in. canister holding 28.5 lbs of lithium hydroxide, and blower were placed inside the test chamber and the test was conducted in much the same manner as were the simulated occupancy passive absorption tests. This test was conducted at 85°F ET.

Figure 5 EXPERIMENTAL SET-UP FOR SECOND ACTIVE ABSORPTION TEST

3.1.2.2 Test Results - Results of the first active system test (soda-lime canister are presented graphically in Figure 6. A breakthrough is shown to occur after about only 10 hours of operation, which indicates that less than 9.6 lbs of carbon dioxide were absorbed. Actually, weight measurements show that only 5 lbs of carbon dioxide were absorbed by the 61 lbs of soda-lime. Using equation (2) rearranged the utilization efficiency was calulated.

$$\eta_u = \frac{m_{CO_2} N t}{V_a A_T \rho_a}, \text{ with } V_a A_T \rho_a = 61 \text{ lbs}$$

$$= \frac{(.1)(10)(10)}{61 \text{ lbs}} = 16.6\%$$

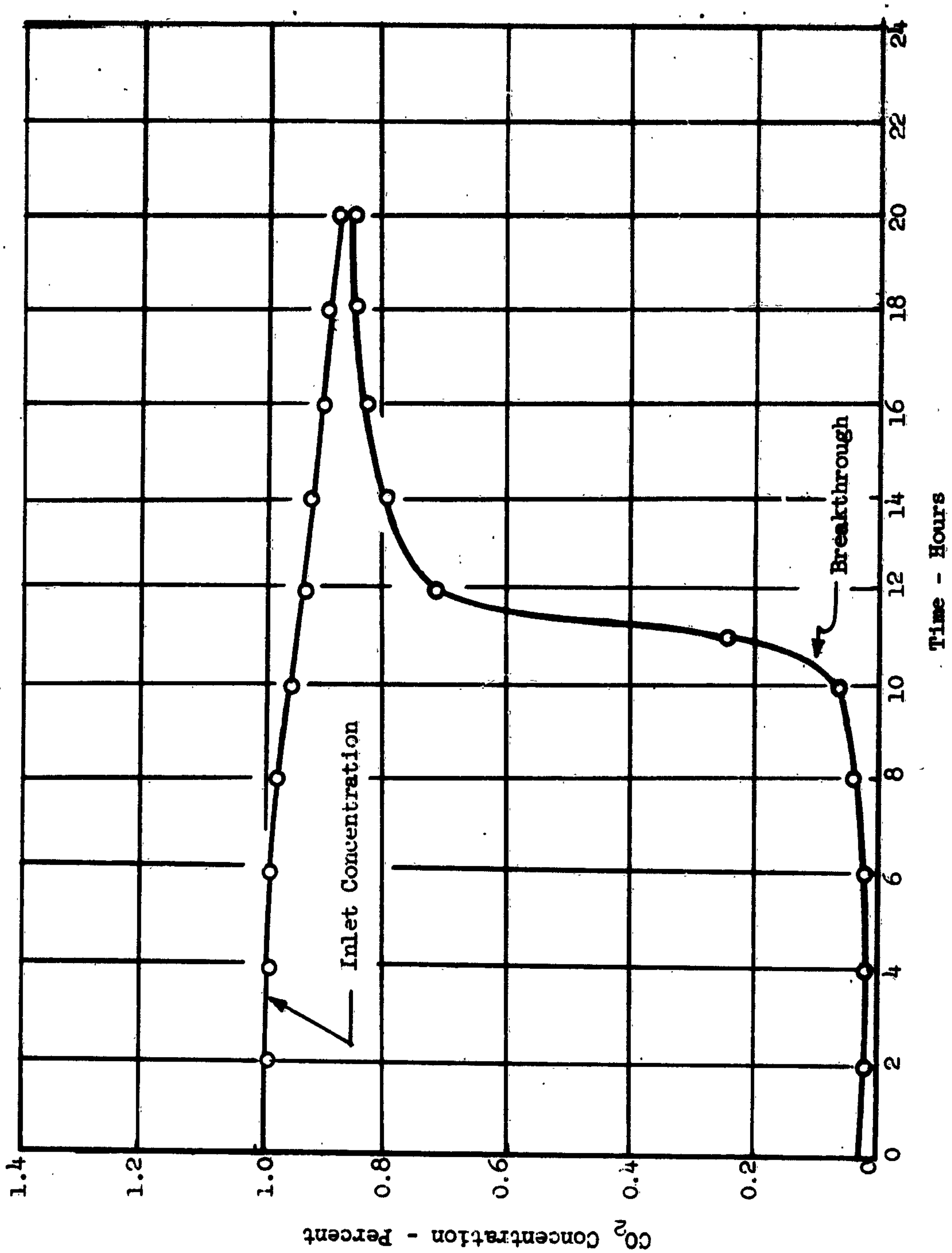

Figure 6 EFFLUENT CO_2 CONCENTRATION VS. TIME FOR FIRST ACTIVE ABSORPTION TEST

It is difficult to assign the cause for the low utilization efficiency obtained. Apparently, the low relative humidity (24 per cent) of the inlet air was the reason for the poor efficiency. More tests would be required before any definite conclusions could be made.

Results of the second active system test (anhydrous lithium hydroxide) were more encouraging as shown in Figure 7. However, it is noteworthy that this test was conducted inside the chamber with relative humidities in the range of 80 to 90 per cent. In this test the carbon dioxide concentration had increased to only 0.4 per cent after 30 hours of operation, thus indicating that approximately 15.6 lbs of carbon dioxide had been absorbed. The calculation using equation (4) is presented below:

$$
\begin{aligned}
W_c &= v_{CO_2} t \quad - C V \rho \\
&= (6\ \text{ft}^3/\text{hr})(30\ \text{hours})(0.114\ \text{lb/ft}^3) \\
&\quad - (0.004)(875\ \text{ft}^3)(0.114\ \text{lb/ft}^3) \\
&= 16.6\ \text{lbs of } CO_2 \text{ absorbed}
\end{aligned}
$$

The efficiency for this test was calculated to be 0.56, as shown below.

$$
\begin{aligned}
\eta_u &= \frac{\text{wt of } CO_2 \text{ absorbed}}{V_a A_T \rho_a} \\
&= \frac{16.6\ \text{lbs}}{1.27\ \text{ft}^3 \times 0.92 \times 24\ \text{lbs/ft}^3} \\
&= 0.6
\end{aligned}
$$

These tests show that a factor of safety of at least 2:1 should be taken in all canister designs to allow for less than anticipated performance.

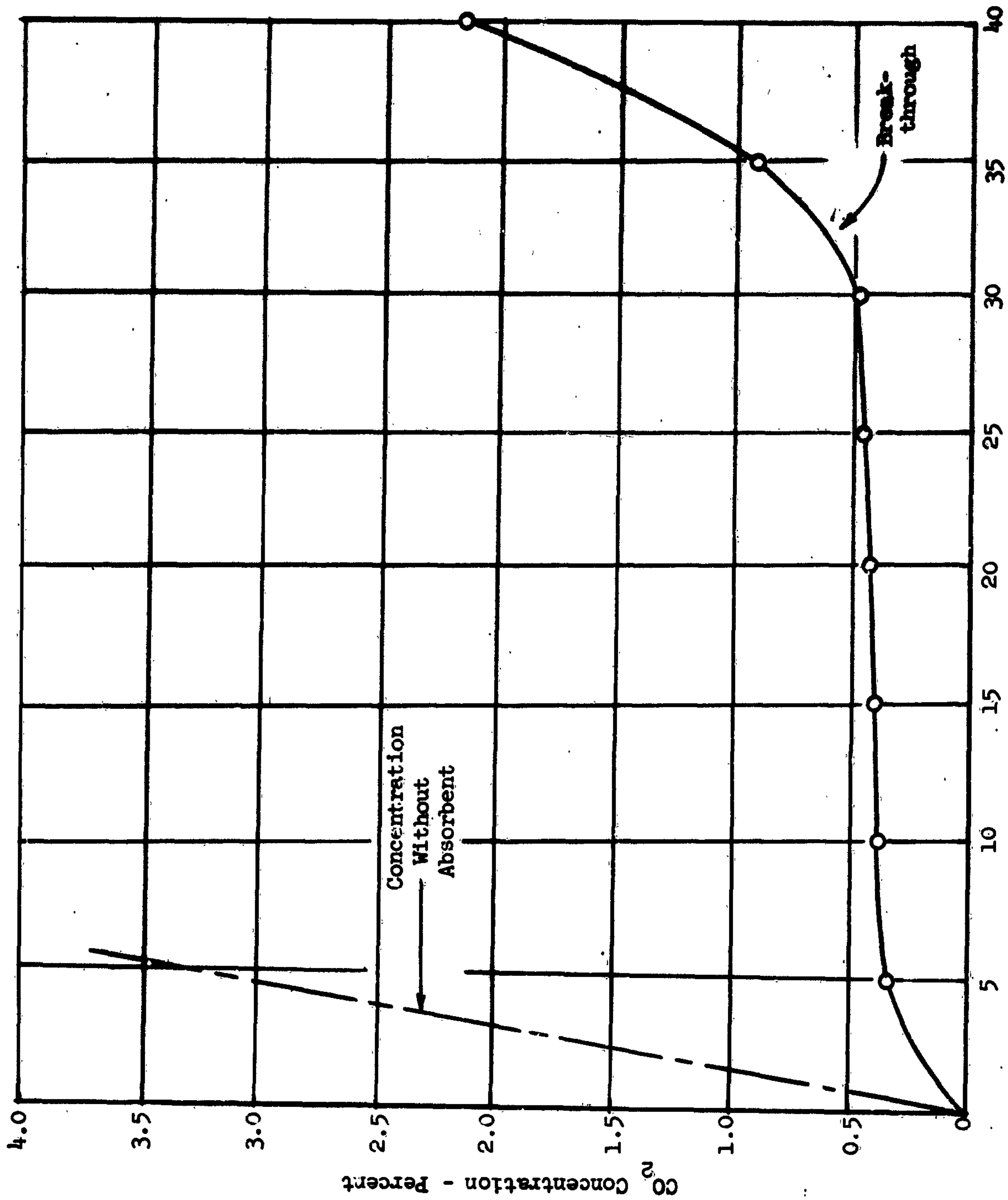

Figure 7 CHAMBER CO_2 CONCENTRATION VS. TIME FOR SECOND ACTIVE ABSORPTION TEST

3.2 Human Occupancy Test

On February 25, 1964 an eight-hour human occupancy test was conducted in the 1000-cubic foot underground shelter located adjacent to the MRD parking lot. The walls had been coated with a thermosetting plastic paint to preclude CO_2 absorption on the walls. The purpose of this test was to provide data for a realistic comparison with the results obtained in the simulated occupancy tests and to delineate areas in need of further research and/or development effort.

3.2.1 Test Apparatus

Figures 8 and 9 depict the test configuration used in the manned test. Figure 8 shows that the set-up and instrumentation was similar to that used during the unmanned tests.

Eight one-half-inch beds of Baralyme were suspended near the ceiling (see Figure 9). Concentration was again measured and recorded by a MSA Lira Infrared CO_2 Sensor and a Leeds and Northrup Type G Strip Chart Recorder which were located in the ground-level instrument room. The same diaphragm pump was used to draw shelter air samples from any of three locations. A Brown Instruments Multipoint Recorder was used in conjunction with copper-constantan thermocouples to measure and record temperatures at ten points including soil temperature and wet bulb temperature.

To supply breathing oxygen to the five occupants, one standard 244-cubic foot (STP) oxygen cylinder was equipped with a twenty-five-dollar Bastian-Blessing Company single-stage oxygen regulator. A Brooks-Mite Rotameter with valve was used to control the rate of oxygen flow and a Beckman Instrument Company Polaragraphic Model 777 Oxygen Analyzer was used to indicate the concentration of oxygen (see Figure 9).

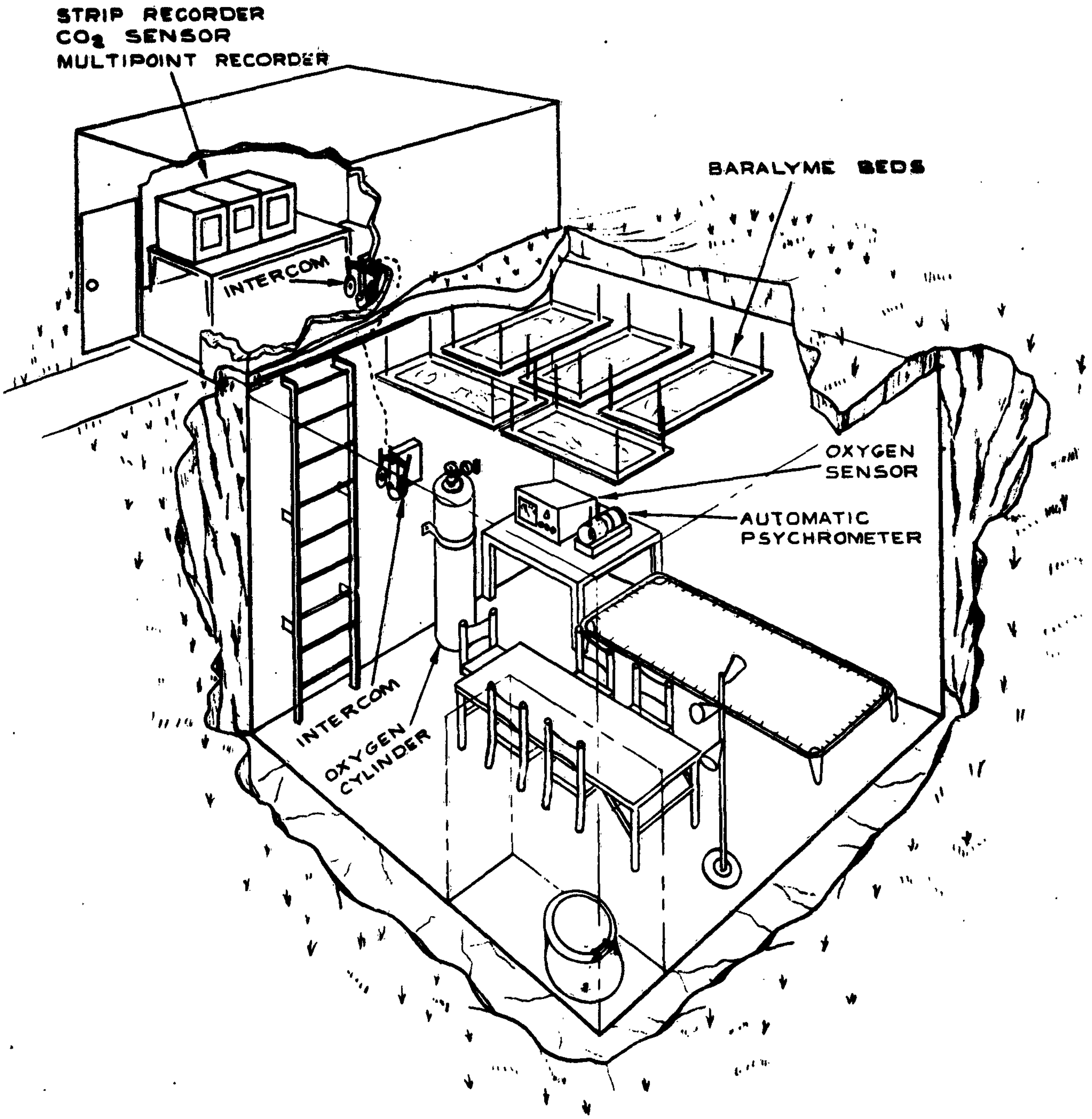

Figure 8 TEST CONFIGUATION FOR HUMAN OCCUPANCY EXPERIMENT

The shelter was also equipped with a table, chairs, a lamp, and a sleeping cot for the comfort of the occupants. Toilet facilities were also provided.

3.2.2 Test Procedures

The five male volunteers entered the shelter at 0900 hours and the trap door was not opened until 1700 hours that same day. Age, weight and heights of each volunteer is presented below. Figure 9 shows each volunteer at the start and at the completion of the 8-hour test.

Number	Age	Height	Weight
1	28 yrs.	70 in.	165 lbs.
2	21	71	165
3	26	71	160
4	25	57	175
5	27	70	195
50-percentile man		59	155

The only task required of the occupants was to report the oxygen concentration every one-half hour over the intercom, since a recording or read-out device was not provided in the instrument room. During the last hour the occupants were required to take turns in fanning the Baralyme beds with a large piece of stiff cardboard to determine the magnitude of this effect upon carbon dioxide concentration. Respiration rates were also taken sporadically by the occupants and reported to the instrument room as a crude check upon their physiological and psychological conditions.

Baralyme Beds in Position

Oxygen Supply and Sensor

Volunteers at Start of Test

Volunteers at End of Test

FIGURE 9 HUMAN OCCUPANCY TEST PHOTOGRAPHS

3.2.3 Test Results

The results of the human occupancy can best be described by reference to Table 7. This data is also presented in graph form in Figure 10. In general, the results were very encouraging. As shown, the concentration of carbon dioxide never exceeded 0.9 percent which is considered well below the human tolerance level. The respiration rates also confirm that the concentration never attained a value high enough to cause an increase in respiration. This would have been the most notable physiological change occurring because of too high a concentration of carbon dioxide.

Even though a direct measure of carbon dioxide production could not be obtained it may be estimated from the oxygen consumption. Oxygen flow from the cylinder was 4 cfh for eight hours or 32 cubic feet. Oxygen concentration decreased from 20.8 per cent to 19 per cent which accounts for 18 cubic feet (1.8% x 1000 cubic feet). Thus, a total of 50 cubic feet of oxygen were consumed during eight hours by five men for an average consumption rate of 1.25 cubic ft/man-hr. This value is higher than the value commonly reported for the average man under sedintary activity. Nevertheless, 1.25 is a reasonable value when one considers that all occupants were larger and/or heavier than the average man as shown in Section 3.2.2.

Assuming a respiratory quotient of 0.82, a carbon dioxide production rate of slightly over 1 cubic ft/man-hr is obtained. Therefore, the concentration of carbon dioxide would have reached a value of 4 per cent in eight hours had no absorbent been present.

Table 7 SUMMARY OF ENVIRONMENTAL PARAMETER DATA FOR HUMAN OCCUPANCY TEST

TEST NO. 40
DATE 2/15/64
ABSORB. TYPE Baralyme
ABSORB. AMOUNT 5 Rocks - 40 lbs.
CIRCULATION TYPE Passive

NO. OF PEOPLE 5
EXPECTED CO_2 RATE 5 cfm
CO_2 SAMPLING FLOW 2 cfm
APPARENT CO_2 RATE 5 cfm
APPARENT O_2 RATE 6.25 cfm

Time	DBT[1] °F	WBT[1] °F	% RH[1]	Soil Temp.[2] °F	Content.[3] CO_2 - %	Content.[3] O_2 - %	Remarks
0900	64.3	52.5	45	39.3	0.16	20.8	Playing Cards
1000	70.0	63.8	71	39.3	0.31	19.9	Talking
1100	67.4	61.5	72	39.2	0.43	19.5	Rest. Rate 14/min.
1200	67.8	62.8	77	39.3	0.50	19.5	Eating
1300	68.0	63.8	80	39.6	0.60	19.4	Playing Cards Calabrate OK
1400	68.3	64.3	81	39.5	0.73	19.2	Resp. Rate 16/min.
1500	68.6	64.8	83	39.5	0.83	19.05	Slight discomfort in taking deep breath
1600	68.5	64.8	83	39.4	0.80	19.1	Started Fanning beds
1700	68.9	65.2	83	39.6	0.60	19.0	Test stopped as scheduled

1. Dry bulb temperature, wet bulb temperature, relative humidity in shelter
2. Soil temperature three feet under ground level, and six feet from outside of shelter wall
3. Average CO_2 and O_2 concentrations in shelter

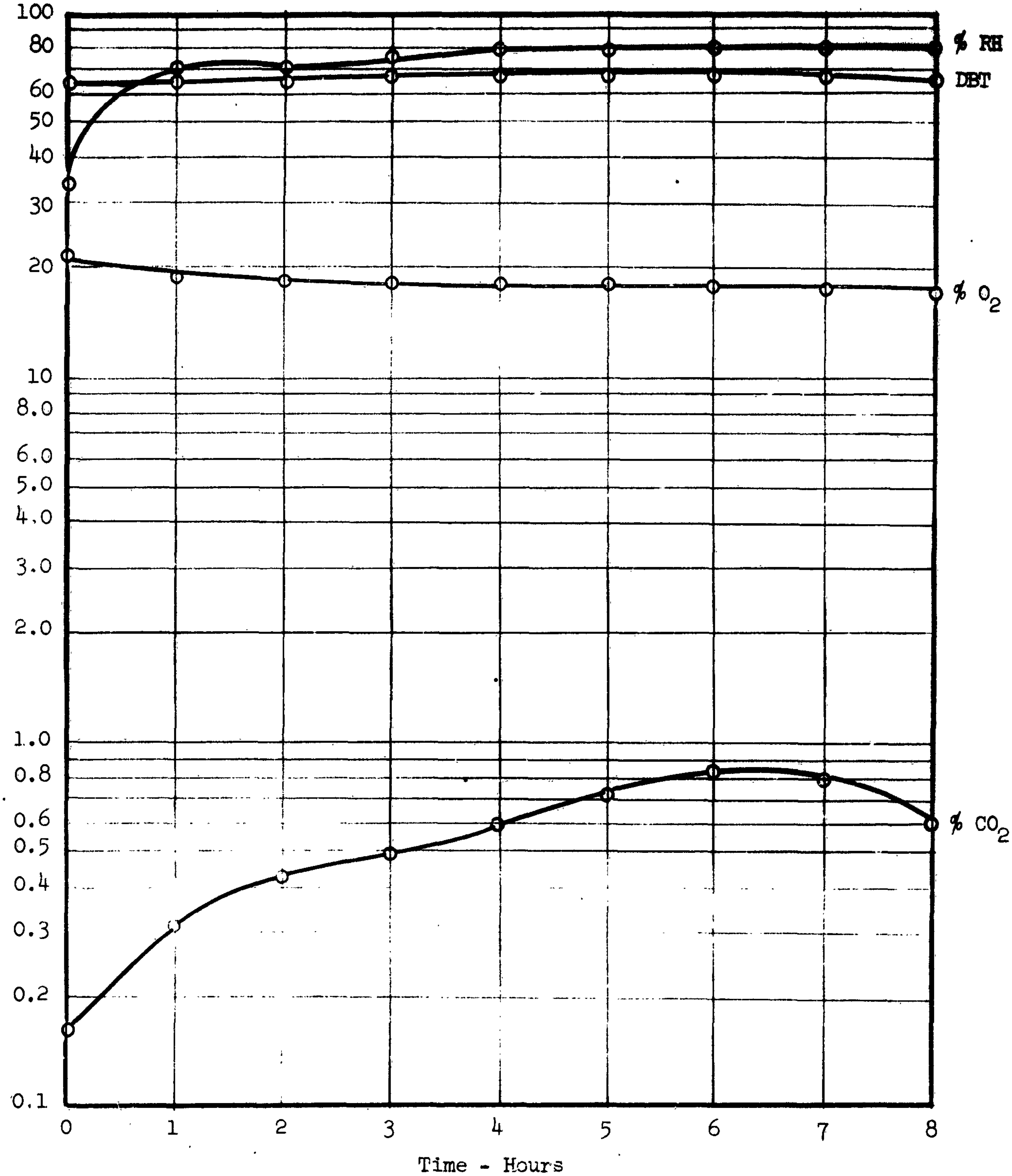

Figure 10 PLOT OF ENVIRONMENTAL PARAMETERS FOR HUMAN OCCUPANCY TEST

Special attention is called to the last hour of the test as depicted in Figure 10. The decrease in concentration from 0.83 per cent to 0.6 per cent demonstrated vividly the effect of higher air circulation rates upon absorbent bed performance as was previously mentioned and discussed under Section 3.1.1.3. It is also noteworthy that no measurable statification of carbon dioxide occurred during this test even though no fans were used to circulate the air. In other words, body movements, natural convection currents, and diffusion rates were sufficient to provide adequate circulation to prevent statification.

Figure 10 also shows that relative humidity reached an equilibrium value of 82 per cent when the dew point of shelter air reached the apparent temperature of the shelter walls and condensation began. Dry bulb temperature was noted to increase only slightly to its steady state value of 70°F.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 General

When toxic gases from any source are present in the proximate atmosphere, a shelter must be either well sealed or slightly pressurized to prevent infiltration or diffusion into occupied spaces. If pressurization is employed it should be sufficient to counteract transient kinetic wind pressures.

If the rate of oxygen supply slightly exceeds the rate of consumption, a progressive increase in oxygen partial pressure will result. One may assume that only a slight increase in total pressure would occur until exfiltration occurs, even in relatively well-sealed shelters. Even so, oxygen concentration and partial pressure will increase since carbon dioxide would be absorbed and nitrogen displaced. Conversely, if the oxygen supply rate is slightly deficient, a small amount of outside air may infiltrate the shelter. The effect of a slight oversupply of oxygen is obviously not as potentially dangerous as an undersupply, especially for periods as short as 24 hours. For this reason, a slight oversupply of oxygen should be recommended.

Life support systems would seem to have limited applicability in unmodified "identified" fallout shelters - at least until other substantial problems are solved; for example, fire resistance and infiltration of outside air. Therefore, other types of shelters must be considered for use with life support systems.

4.2 Cost Effectiveness

The final report for the study program contained estimates of per person costs to provide environmental control in various sized shelters. The new information obtained during the test program allows a revision of the previous estimates to the final estimates presented herein.

4.2.1 Oxygen Supply Method

The total cost for oxygen supply includes the cost of the regulators, cylinders (plus the stored oxygen), and any distribution or diffusing equipment, if used. By using a regulator such as the type proposed by Bastian-Blessing Co., the cost for a regulator would be only $0.08 per person for 100-man shelters. Total oxygen required for 100 man-days would be 2400 cubic feet (STP) at a cost of $0.60 per person. If six 400-cubic foot capacity cylinders were used then the prorated cylinder charge would be $4.00 per person for a total cost of $4.68 per person.

The larger shelters (1000-man) would use multiple units of the 200-person regulator suggested by Scott Aviation Corp. Scott could not quote a firm price for such a regulator but the per-person cost should be less than that of the 100 man Bastian-Blessing regulator. The use of larger storage cylinders for 100-man shelters (say sixteen 1500-cubic foot cylinders) would result in a per-person cost of only $3.58 per person for storage. Oxygen costs of $0.50 per person in large quantities would result in a total per person cost of approximately $4.13 for oxygen supply in very large shelters.

It should again be emphasized, as was previously stated in Section 2.2, that the type of oxygen supply equipment selected is dependent upon the size and type of shelter. If distribution and diffusion equipment, as mentioned by Linde Co,. is considered advisable for a particular shelter, the costs would be correspondingly higher. The use of an oxygen sensor is also strongly recommended to aid in controlling the oxygen flow rate.

4.2.2 Carbon Dioxide Absorption Methods

The experimental results obtained have shown that carbon dioxide absorbents can be used just as efficiently in screened panels as in canisters. The use of either method would result in sensible heat gains in the amounts specified in sections 2.1.1.1 or 2.1.1.2. The most significan drawback to either method is that there is no assurance that the carbon dioxide concentration is being maintained at safe levels. The use of a carbon dioxide sensor in conjunction with either method is therefore strongly advocated, especially for large shelters.

Since the screened panel, passive absorption method does not require a blower it is less expensive than the canister system, and therefore superior on a cost-effectiveness basis of comparison. However, the screened panel method is not considered as reliable as is the canister method. The screened panel method does inherently possess a factor-of safety in that the shelter occupants may "fan" the absorbent if the assurance of higher performance is desired. The effectiveness of this technique was demonstrated in the human occupancy tests. (See Section 3.2.)

Based on the results of the test program the following recommendations are offered:

1. At least eight (8) pounds of Baralyme should be used for each person in the shelter (for a 24-hour period).

2. The Baralyme should preferably be preloaded in a manufactured plastic-coated 12-mesh screened panel to a thickness of 1/4-inch, thus occupying eight (8) square feet of area (2.84 ft x 2.84 ft, for example) for each person.

3. If space is at a premium, the Baralyme may be preloaded to a thickness of 1/2-inch, in a panel only four (4) square feet in area.

4. The screens should be positioned just above head level or at least two feet from the ceiling, if convenient.

5. If screens are not available (and it is desired to spread the Baralyme on blankets, bedsheets etc.) the weight requirement should be increased to twenty (20) pounds per person. If a thickness of 1/2-inch is used (1/4-inch is again preferred) an area of ten (10) square feet per person is required.

6. Soda-lime may be used as the absorbent with a slight decrement (15 per cent) in performance, but the use of anhydrous lithium hydroxide is definitely prohibited because of the tendency to dust.

7. Per person costs for 24-hour durations are shown below:

   Method 2 - \$2.88 (Baralyme) + \$1.50 (panel) = \$4.38

   Method 3 - \$2.88 (Baralyme) + \$1.00 (panel) = \$3.88

   Method 5 - \$7.20 (Baralyme) + \$0.00 (panel) = \$7.20

These costs may be multiplied by the number of shelter occupants to obtain total costs. Use of soda-lime would result in slightly lower total costs but would require more space.

4.3 Recommendations for Further Study

In view of the information obtained in both the study and the test program further research along the lines described below appears appropriate.

4.3.1 Oxygen Supply

An extensive operations-analysis-type-of-study is suggested in order to delineate more accurately the costs of providing oxygen supply for closed shelters. This type of information would allow an analysis of the combinations of the various sizes and types of regulators, cylinders, and distribution systems. This study would result in specifications, costs, and installation designs for providing oxygen supply in a series of fallout shelters.

4.3.2 Carbon Dioxide Absorption

Quantitative data relative to the use of passive absorption systems for carbon dioxide control has been obtained. However, this data was gathered mainly from simulated occupancy tests. Only one small scale human occupancy test was conducted as described in this report. In order to recommend carbon dioxide removal systems for the large shelters a scale-up factor of 100:1 to 300:1 is required.

A full-scale human occupancy test of passive absorption methods is suggested in order to provide more reliable design and installation information. Preliminary tests would be conducted in the OCD underground shelter at MRD. These initial tests would use five occupants as did the human occupancy test described in this report but the duration of the tests would be extended to 24 hours.

Based on the data obtained from such tests, the full-scale test program would investigate the reliability of the design data obtained by conducting tests in large shelters using perhaps 100 or more volunteers. These large-scale tests

will then enable the specification of production, packaging and installation data for screened absorbent panels.

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Copy No. ____

Shelter Research 1400 - Component Development, Subtask 1424 A- Experimental Study of Life Support in Closed Shelters

Summary

of

Research Report

EXPERIMENTAL EVALUATION OF ENVIRONMENTAL CONTROL SYSTEMS FOR CLOSED SHELTERS

July 1964

This report has been approved in the Office of Civil Defense and Approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

Contract No. OCD-PS-64-6

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1.0 Introduction

1.1 Background

This program was initiated as a follow-on to Contract OCD-OS-62-56 and entailed the testing and evaluation of methods for controlling the oxygen and carbon dioxide content of a closed shelter.

The earlier program was a feasibility and parametric study of atmosphere control techniques for use in closed underground shelters, with respect to projected cost-effectiveness, as well as a state-of-the-art survey. Life support systems are required whenever the presence of outside fires precludes the supply of ambient air to the shelter. Environmental control systems which were evaluated under the earlier program included all conceivable types of oxygen supply, carbon dioxide and toxic and/odiferous constituent removal, and temperature-humidity control.

1.2 Objectives and Scope

The objectives of this present contract, hereinafter referred to as the test program, were, in large part, stipulated under the previously referred to contract, hereinafter referred to as the study program.

The study program indicated that three solid absorbents; namely, lithium hydroxide (anhydrous), Baralyme, and soda-lime, are best suited for controlling the concentration of carbon dioxide within a closed shelter. Strope and others demonstrated the efficacy of the use of Baralyme for controlling carbon dioxide concentrations in shelters during manned occupancy tests at the U. S. Naval Radiological Defense Laboratory in 1959.

The study program also indicated that from a standpoint of safety, reliability, and ease of handling, breathing oxygen should be supplied by either chlorate candles or high pressure gas cylinders equipped with a regulator and small flowmeter. Since the gas cylinder method is less expensive than the use of chlorate candles, the cylinder method was recommended for all shelters occupied by more than five persons.

Based on the above findings it was decided that the test program should experimentally evaluate the performance of solid carbon dioxide absorbents to obtain design information for shelter use. As a further delineation of the program objectives, it was decided that the main emphasis should be placed upon passive absorption methods, since these methods seemed more likely to be used than dynamic systems, which require power. Also, the state-of-the-art, relative to passive absorption phenomenon, was considered less advanced than that for dynamic absorption techniques.

The study program also concluded that the equipment presently available for dispensing oxygen from large high pressure storage bottles is not only too expensive but too complicated for use by the average citizen, especially during periods of high emotional stress. Therefore, it was decided to contact a number of manufacturers of gas regulating equipment to explore the possibility of the commercial development of a closed shelter oxygen regulator - if and when the procurement order might be given.

The listing below reiterates and summarizes the program objectives.

1. Determine design parameters for the use of passive carbon dioxide absorption techniques in closed shelters.

2. Verify the design information for dynamic absorption methods stated in the study contract.

3. Conduct a field survey of regulator manufacturers to learn of possible design changes which would yield a regulator more adaptable to fallout shelter use.

As a final test the best passive absorbent and most suitable oxygen regulator were to be tested in a human occupancy test. Simulated occupancy tests for carbon dioxide absorption were to be conducted in an 875-cubic foot environmental chamber, and the human occupancy test in a 1000-cubic foot underground shelter.

2.0 CO_2 Absorption Tests

Passive absorption systems were utilized in both the simulated and human occupancy tests.

2.1 Simulated Occupancy Tests

2.1.1 Test Apparatus - Figure 1 shows the test configuration utilized during all simulated occupancy tests. Since the main portion of the environmental test chamber was approximately 500 cubic feet in volume (excluding the volume of the air lock) a nominal manned capacity of six men (allowing a per person free volume of 85 cubic feet) was assigned to the chamber. Assuming a carbon dioxide production rate of 0.85 cubic ft/hr per person a carbon dioxide flow rate of about 5 cfh was established for all tests with the exception of tests numbered 36 and 37.

The carbon dioxide was released into the chamber by means of a length of flexible tubing with several pin holes so as to diffuse the gas flow, and thereby reduce the magnitude of forced convection currents.

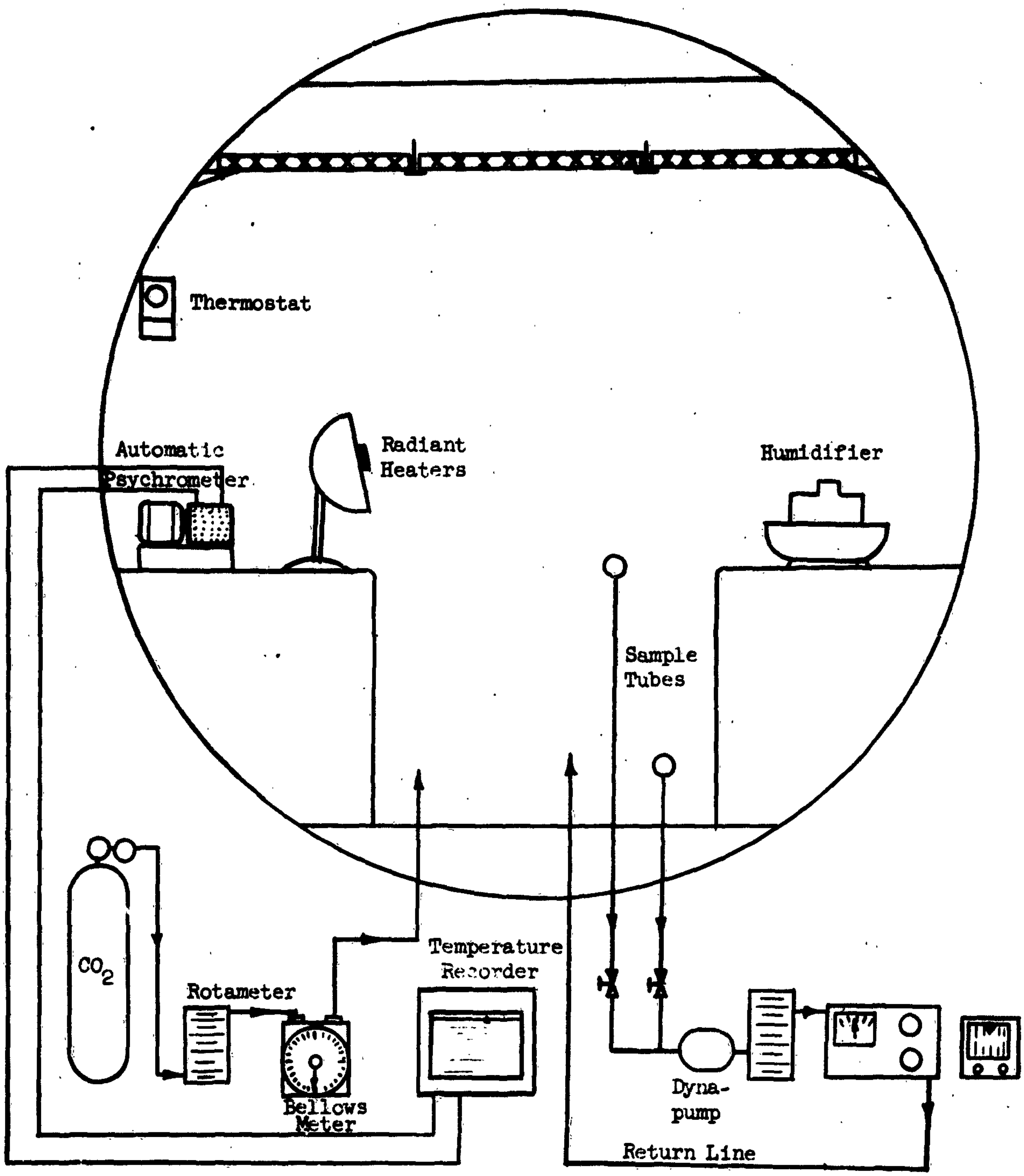

Figure 1 EXPERIMENTAL SET-UP FOR SIMULATED OCCUPANCY PASSIVE ABSORPTION TESTS

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A Brooks Purge Meter was used to control the rate of flow at 5 cfh and a Sprague Bellows Meter was used to measure total flow. Concentration of carbon dioxide was measured by means of a MSA Lira Infrared CO_2 Sensor (0 to 4 per cent) and continuously recorded on a Leeds and Northrup Type G Strip Chart Recorder. A small diaphragm pump was used to draw and return a sample of gas from either of two locations in the test chamber.

Electric radiant heaters controlled by a thermostat and both atomizing and vaporizing humidifiers were incorporated to maintain the required effective temperature of 85°F. A Brown Instruments Multipoint Recorder was used in conjunction with thermocouples and an automatic psychrometer to provide a permanent record of temperature and relative humidity.

The absorbent beds consisted of simple wooden frames with 1/4-mesh fiber-glass coated screens. Dimensions of the effective area were 1.5 feet by 2.5 feet. As an example, these frames were capable of holding 8 pounds of Baralyme when it was spread to a thickness of 1/2-inch.

2.1.2 Test Procedures and Results

Matrices representing the test parameters in the simulated occupancy tests are presented as Tables 1 and 2. A typical plot (for test No. 7) of chamber CO_2 concentration versus time appears as Figure 2. Summary data for all tests is presented in Table 3. As shown, the second series of tests was conducted using Baralyme only because the initial tests indicated the superiority of this absorbent.

2.2 Human Occupancy Tests

On February 25, 1964 an eight-hour human occupancy test was conducted in the 1000-cu. ft. underground shelter located adjacent to the MRD parking lot. Five male volunteers were employed in this test.

TABLE 1

DESCRIPTION MATRIX FOR INITIAL SERIES OF PASSIVE ABSORPTION TESTS

All tests conducted at 85°F ET with absorbent spread 1/2-inch thick and minimal air circulation.

		Absorbent		
Area	Position	LiOH	Baralyme	Soda-Lime
One Bed	Lower	1, 2	24	23
	Upper	3	20	17
Two Beds	Lower	29	8, 9	22
	Upper	18	19	21
Three Beds	Lower	10	5, 6, 7	14, 15
	Upper	18	11	13, 16

TABLE 2 DESCRIPTION MATRIX FOR SECOND SERIES OF PASSIVE ABSORPTION TESTS

All tests conducted at 85°F ET with Baralyme

	Thickness		
Area	1/4"	1/2"	3/4"
One Bed	30, 32	(20)	31
Two Beds	27, 33*	(19) 35*	28
Three Beds	25	(11)	34

*Signifies starting condition of 72°F DBT and 58°F WBT

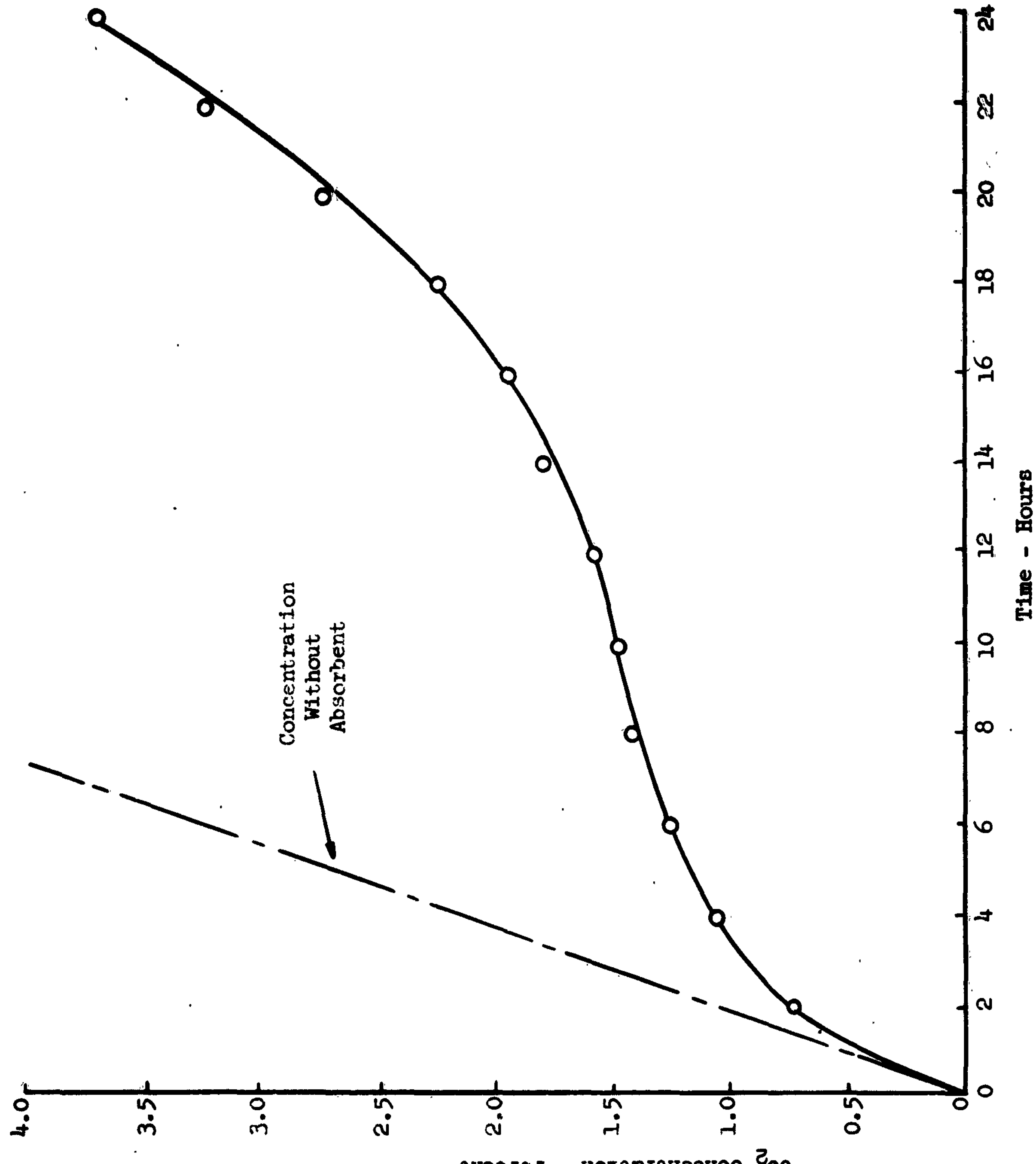

Figure 2 CHAMBER CO_2 CONCENTRATION VS. TIME FOR TEST NO. 7

Table 3 SUMMARY DATA FOR PASSIVE ABSORPTION TESTS

Test No.	Average CO_2 Flow Rate (cfh)	Hours to Reach CO_2 Concentrations				
		0.5%	1.0%	2.0%	3.0%	4.0%
1	4.62	0.5	1.5	3.25	5.0	7.0
2	4.9	0.75	1.75	----	---	---
3	4.9	0.8	1.75	----	---	---
4	4.9	0.75	1.7	Calibration Check		
5	5.0	0.95	2.75	----	---	---
6	5.0	1.0	2.75			
7	4.63	0.55	1.75	16.5	21.3	24.75
8	5.05	1.3	2.2	7.25	13.4	17.0
9	5.4	1.0	2.25	9.25	16.25	20.5
10	5.48	0.9	3.25	15.25	-----	------
11	4.79	1.1	5.5	17.25	21.25	24.75
12	4.92	1.1	4.0	19.0	26.75	33.0
13	5.02	0.75	2.0	6.5	11.4	-----
14	4.93	0.75	1.9	6.5	11.75	17.6
15	4.96	0.95	3.0	12.5	16.85	20.0
16	4.86	1.0	3.5	15.0	20.0	23.5
17	5.05	0.75	1.95	4.75	8.4	11.75
18	5.11	0.9	2.25	9.0	16.5	22.2
19	4.96	0.9	2.45	10.25	15.1	18.0
20	4.96	0.75	1.85	4.7	8.4	12.0
21	5.02	0.9	2.6	10.25	14.4	17.3
22	4.88	0.9	2.4	8.75	14.1	17.1
23	4.96	0.7	1.7	4.4	7.9	11.25
24	4.85	0.85	2.0	5.2	8.75	12.0
25	5.88	0.80	2.8	9.75	12.5	15.75
27*	5.33	0.95	2.7	7.0	9.9	11.25
28	4.82	0.8	2.5	9.55	16.0	20.9
29	4.97	0.8	2.2	8.2	16.9	23.2
30	5.00	0.6	1.6	4.3	7.0	9.25
31	5.37	0.9	2.0	5.1	9.5	14.1
32	5.01	0.65	1.7	4.3	6.9	9.25
33	4.94	0.9	2.25	6.5	10.35	13.0
34	5.04	0.9	2.6	15.5	27.0	32.5
35	4.79	0.8	2.05	6.6	15.0	19.4
36	9.88	0.5	1.0	2.5	4.5	7.5
37	10.0	0.95	2.0	4.55	6.65	8.5

* Test No. 26 was a canister test

2.2.1 Test Apparatus - Figure 2 shows that the test set-up and instrumentation was similar to that used in the unmanned tests.

Eight one-half-inch beds of Baralyme were suspended near the ceiling. Concentration was again measured and recorded by a MSA Lira Infrared CO_2 Sensor and a Leeds and Northrup Type G Strip Chart Recorder which were located in the ground-level instrument room. This same diaphragm pump was used to draw shelter air samples from any of three locations. A Brown Instruments' Multipoint Recorder was used in conjunction with copper-constantan thermocouples to measure and record temperatures at ten points including soil temperature and wet bulb temperature.

To supply breathing oxygen to the five occupants, one standard 244-cubic foot (STP) oxygen cylinder was equipped with a twenty-five-dollar Bastian-Blessing Company single-stage oxygen regulator. A Brooks-Mite Rotameter with valve was used to control the rate of oxygen flow and a Beckman Instrument Company Polarographic Model 777 Oxygen Analyzer was used to indicate the concentration of oxygen.

The shelter was also equipped with a table, chairs, a lamp, and a sleeping cot for the comfort of the occupants. Toilet facilities were also provided.

2.2.2 Test Results - The results of the human occupancy test can best be represented by reference to Figure 3. As shown, the concentration of carbon dioxide never exceeded 0.9 per cent which is considered well below human tolerance level. Without absorption of CO_2 the concentration would have increased to nearly 4 per cent. Special attention is called to the last hour of the test as depicted in Figure 3. The decrease in CO_2 concentration was created by instructing the volunteers to "fan" the absorbent beds with large sheets of cardboard, thus vividly demonstrating the beneficial effects of higher air circulation rates upon absorption by screened panels.

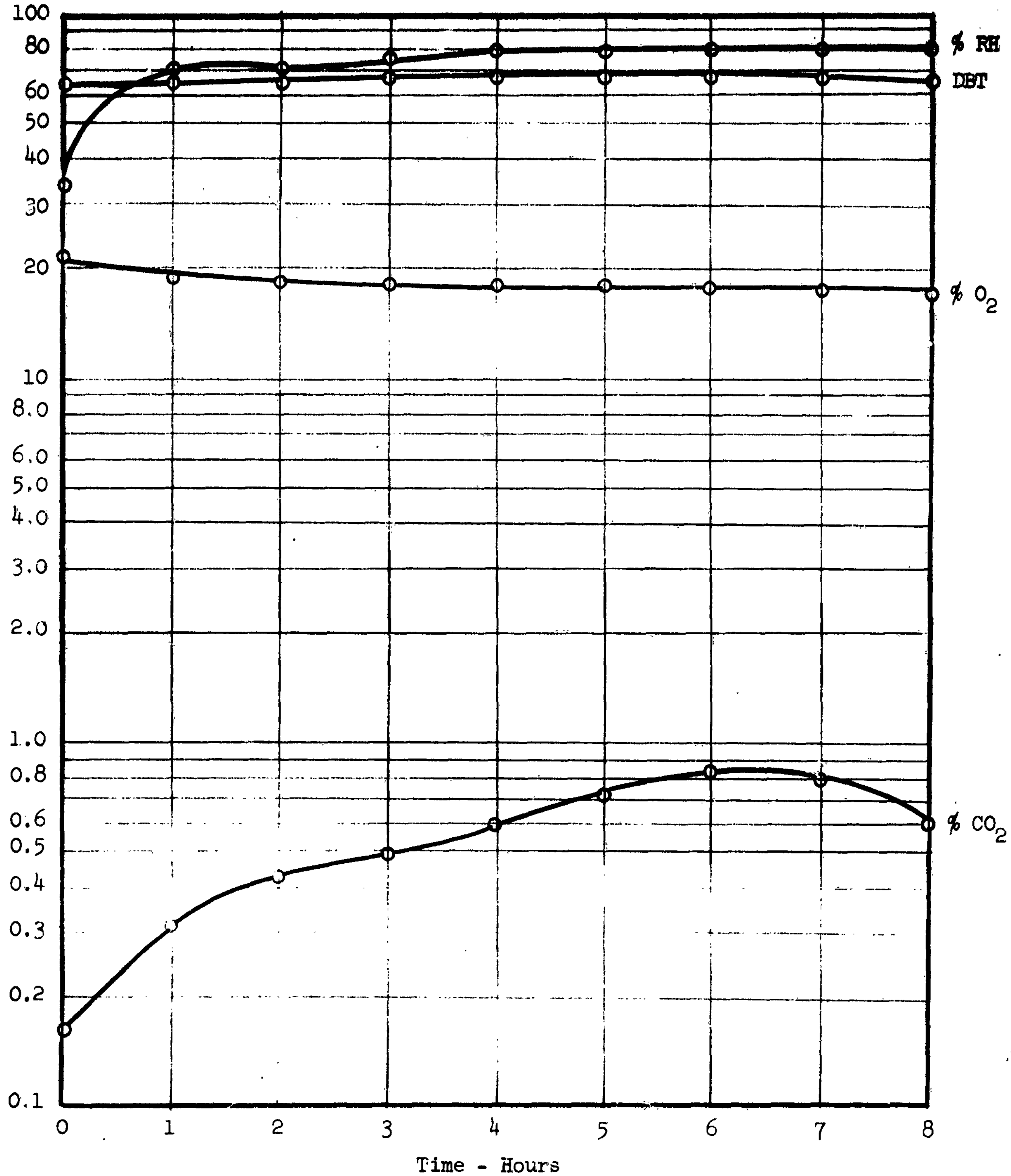

Figure 3 PLOT OF ENVIRONMENTAL PARAMETERS FOR HUMAN OCCUPANCY TESTS

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3.0 Conclusions

3.1 Oxygen Supply

The total cost for oxygen supply includes the cost of the regulators, cylinders (plus the stored oxygen), and any distribution or diffusing equipment, if used. By using a regulator such as the type proposed by Bastian-Blessing Co., the cost for a regulator would be only $0.08 per person for 100-man shelters. Total oxygen required for 100 man-days would be 2400 cubic feet (STP) at a cost of $0.60 per person. If six 400-cubic foot capacity cylinders were used then the prorated cylinder charge would be $4.00 per person for a total cost of $4.68 per person.

The larger shelters (1000-man) would use multiple units of the 200-person regulator suggested by Scott Aviation Corp. Scott could not quote a firm price for such a regulator but the per-person cost should be less than that of the 100-man Bastian-Blessing regulator. The use of larger storage cylinders for 1000-man shelters (say sixteen 1500-cubic foot cylinders) would result in a per-person cost of only $3.58 per person for storage. Oxygen costs of $0.50 per person in large quantities would result in a total per-person cost of approximately $4.13 for oxygen supply in very large shelters.

3.2 Carbon Dioxide Control

Based on the results of the test program the following recommendations are offered:

1. At least eight (8) pounds of Baralyme should be used for each person in the shelter (for a 24-hour period).

2. The Baralyme should preferably be preloaded in a manufactured plastic coated 12-mesh screened panel to a thickness of 1/4-inch, thus occupying eight (8) square feet of area (2.84 ft x 2.84 ft, for example) for each person.

3. If space is at a premium, the Baralyme may be preloaded to a thickness of 1/2-inch, in a panel only four (4) square feet of area.

4. The screens should be positioned just above head level or at least two feet from the ceiling, if convenient.

5. If screens are not available (and it is desired to spread the Baralyme on blankets, bedsheets etc.) the weight requirement should be increased to twenty (20) pounds per person. If a thickness of 1/2-inch is used (1/4-inch is again preferred) an area of ten (10) square feet per person is required.

6. Soda-lime may be used as the absorbent with a slight decrement (15 per cent) in performance, but the use of anhydrous lithium hydroxide is definitely prohibited because of the tendency to dust.

7. Per person costs for 24-hour durations are shown below:

   Method 2 - \$2.88 (Baralyme) = \$1.50 (panel) = \$4.38

   Method 3 - \$2.88 (Baralyme) = \$1.00 (panel) = \$3.88

   Method 5 - \$7.20 (Baralyme) = \$0.00 (panel) = \$7.20

These costs may be multiplied by the number of shelter occupants to obtain total costs. Use of soda-lime would result in slightly lower total costs but would require more space.